CONFERENCE ON ARTIFICIAL SATELLITES

PART A

VIRGINIA POLYTECHNIC INSTITUTE

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PART A

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ACKNOWLEDGMENTS

The Virginia Polytechnic Institute wishes to acknowledge its indebtedness to the National Science Foundation for providing the funds in support of this conference. Without this support the one hundred faculty members and more than three hundred guests could not have been brought together for the lively discussions and enlightening lectures which prevailed throughout the meetings.

The assistance and guidance of the Steering Committee, and the valuable assistance from staff members of the Langley Research Center and others of the National Aeronautics and Space Administration, is also gratefully acknowledged. Their efforts and their counsel, in a large measure, made the conference the success it was.

The Poly-Scientific Corporation, of Blacksburg, is recognized for its help in providing a tour of the manufacturing facilities and for entertainment for the group.

Lastly, the conference committee members wish to express their personal thanks to those mentioned above and to members of the VPI staff and administration for assistance, cooperation and encouragement through the entire conference operation.

The Conference Committee

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PREFACE

During the last five years with the advent of the artificial satellites, the space research program has developed into one of man's major coordinated scientific and engineering endeavors. It is highly appropriate at this time to look into the results which have been achieved, the plans for the immediate future, and the implications to man's life in the years ahead.

The purpose of this conference is two-fold; one to assist in the interchange of information among scientists and engineers actively working in space research, and, two, to bring information and stimulation to scientists and engineers, particularly in educational institutions, who may not now be engaged in this field. The vast magnitude of the space research effort renders each of these objectives extremely critical. With new discoveries and technological advances coming so rapidly, communication often lags behind. Reports are frequently delayed or lacking. Experts may be unaware of pertinent results by other experts. Even when reports are available, time may limit the feasibility for a scientist or engineer to read, digest, and organize all relevant information Particularly is this difficult for one not actively engaged in a major way in the field. There exist large amounts of raw or partially reduced data which might be profitably utilized by teaching-research people if their interest can be stimulated and if sources of information can be brought before them. Stimulating and informing these people may, perhaps, be even more important in its effect on the students trained by them. It is from the educational institution that the large number of new scientists and engineers so desperately needed in the nation's space research effort must come.

To meet these objectives, the conference will bring together the recognized leaders in the field, from this country and abroad, and others from scientific research centers and educational institutions to acquaint them with the problems, findings and most recent accomplishments of interest. It is felt that this will provide a means for wider dissimination of information and instruction on an advanced level to those attending, especially to the one hundred twenty-five invited scientists and engineers from educational organizations.

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THE EARTH AND ITS ATMOSPHERE

AFTER NOW, WHAT THEN IN SPACE?

BY

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DIRECTOR, OFFICE OF SPACE SCIENCES

WASHINGTON, 25, D. C.

AFTER NOW, WHAT THEN IN SPACE?

By

Homer E. Newell

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INTRODUCTION

It is indeed a pleasure and an honor to have the opportunity to give the introductory lecture to this conference on artificial satellites. The subject of the conference is a matter of very active concern in today's world, and conferences such as this play an important role in speedily disseminating the many scientific and technological results stemming from the space program. Such is the breadth and pace of the space effort that space symposia are remarkably, indeed sometimes amazingly, replete with new and exciting results. It needs but a glance at the program for the present conference to arouse great expectations for the next few days.

In composing an introductory lecture, there is always the task of deciding what the lecture is to do. One can take the traditional approach of reviewing in perspective the broad area to be covered in detail by the speakers to follow. Such an introductory lecture serves a useful purpose of orienting the audience toward the general subject, and of setting the stage for the ensuing papers. However, the use of satellites for exploration, scientific investigation, and applications, although still deserving of the name "new" is no longer an unfamiliar subject. It is not likely, therefore, that this audience needs, or would care to endure, such an orientation lecture.

It would appear more useful to attempt to set the stage for the later talks in a somewhat different fashion. Recognizing that the general subject is a familiar one, and that the individual speakers will through their specific papers illustrate far better the character of current activity in space than can be done in any other way, it would seem useful to take a look at where all that current activity is taking us. If used wisely, to gain perspective, such a look into the future can provide helpful guidance for our conduct of the present.

I propose to ask simply the question, "What's next in space?" and to attempt to search out some possible answers. Before proceeding, however, please permit me a word of caution. Many of the topics touched upon will be in the nature of future possibilities, not present plans for future projects or programs. Decisions will have to be made in the future to select from among the abundance of choices.

My premise, then, is that you are all more or less familiar with what is now under way in the space program. You are aware that scientific investigations are being made with sounding rockets, satellites, and deep-space probes to explore the earth, its atmosphere, and outer space. You know that practical applications of space knowledge and technology, for example, meteorological and communications satellites, are under development.

The entire world is conscious of the man-in-space program, and you, I am sure, are aware of the fact that the primary objective of such a program is to develop the capability of man to operate and do things in space, and that the means by which this is to be accomplished is to send men to the moon.

You are also aware of the fact that the Department of Defense is working on applications of space to developing and maintaining our military strength, that we may never be found wanting in any capability required to maintain our freedom and our safety. Also, many of you are conscious of the fact that this broad activity in space is undergirded by a program of advanced research in fundamental science and technology, carried out both in the National Aeronautics and Space Administration and by the Department of Defense, to ensure our continuing capability to move forward along the most promising avenues of exploration, science, and application.

The outcome of this broad program which occupies the early years of the space age, will be of far reaching consequences for our country and for the world. From the scientific and technological research will come precious additions to our stockpile of knowledge. As the fountainhead of those technical and engineering marvels that fill the scene today, such knowledge is rightly esteemed in today's world. Among those technical and engineering marvels are space applications, both civilian and military, the significance of which can be immediately appreciated.

All of these are very important and valuable outcomes of our investment in space. But more important, far more important, is another outcome.

THE SIGNIFICANCE OF THE PRESENT FOR THE FUTURE IN SPACE

Out of this broad activity in space will come the ability of the United States to use space and to operate in space either as it may choose to do voluntarily or may find itself compelled to operate in its own defense. The development of our ability to operate in space, including manned space flight, gives to our country another dimension in which to meet the challenges--both opportunities and threats--of the future. We can do engineering in space, advance our science in a way that cannot be accomplished at the surface of the earth, and extend the range of practical applications for the benefit of man. And, if necessary, we can thwart the attempts of any enemy to use space against us.

In this day and age we cannot afford to ignore this last point. In our own self interest, and for the safety of our country, we cannot permit others to develop space capabilities that we cannot match, and that may therefore be used disastrously against us.

This is a capability we must have to ensure our survival in the space age as the independent, self-determining nation that our forefathers set us up to be, and that we have always insisted on being.

This is the capability that we shall have from the development of the ability to investigate scientifically with satellites and space probes, from space applications, from the ability to perform manned space flight and manned space operations, from the vast complex of manufacturing and assembly plants, launching complexes, tracking and telemetering facilities, and from the invaluable experience that this initial stage in the space program will give us.

This is the most significant point about the present era in space. This is the most important aspect of the present activity in space.

We are now laying the groundwork for whatever role we may have to play in space in the future. We are ensuring that no one will ever be in a position to use space against us while we, helpless and frustrated through lack of the necessary space capability, have to take what comes.

In evaluating the space program, one must never lose sight of this broad aspect. It is this that gives the effort its urgency, and its compelling nature. The sum total of science, application, technology, manned flight through space, training of manpower, development, construction and operation of facilities, the strengthening of our military position in the world--which add up to our ability to choose our own destiny in space as we have done on earth--that gives to the space program its great value and importance to our total well being.

Those who argue that we should dispense with the frills of science and space exploration, and concentrate on the necessities of military development, forget that we can't really say what the military necessities in space will be. Our crystal ball is not that good, and it would be foolhardy to pretend that it is. We do not wish to develop a Maginot line in space, only to have it flanked by forces of greater flexibility. We need to develop in a broad way our space capability so that we shall have the ability to move in any direction required by future events to meet any threats along whatever lines they may develop.

To do otherwise would be like the person who decides to learn to play the piano, but eschews practice of the fundamentals, and goes directly to learning some difficult piece that he likes. Not only will he have unnecessary difficulties in learning the composition, but once he has learned it that will be all he can play. In contrast, the individual who goes at fundamentals first will, in due time, be able to play in stride not only that piece but also all others of comparable difficulty.

Those who single out any one aspect of the space effort and say that that alone is not worth the required expenditures in money, materials, and manpower, may well be right. Nevertheless, it would not follow that the space program, or even that single aspect, should be junked. For, to repeat, it is the great breadth of the program, its contribution to so many aspects of our scientific and technological strength, in other words, the totality of the space effort, that is so important to us both in the present and for our future.

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Now, having first looked at the future in the broad general terms of the significance of present space activities, let us consider future possibilities in a more specific way. With your permission, I shall confine the discussion to space science. Indeed, one of the principal products of our developing ability to handle ourselves in space is new and exciting scientific knowledge about space.

PLANETS

Artificial satellites have given much information about the gravitational properties of the earth, by enabling the scientist to determine with considerable precision the value of higher harmonics in the earth's gravitational potential. From these, further important information has been deduced about the internal structure of the earth. It is very easy to predict more of the same, the further studies of satellites will give further information about the solid earth and its gravity properties.

But the exciting future of this technique may well be in the study of other bodies of the solar system. The moon is particularly attractive as our nearest neighbor in space, as a triaxial body for which there is considerable uncertainty about the distribution of matter within its volume. Satellites orbiting about the moon will afford the lunar geodesist with a rich harvest of information that he is not likely to obtain in any other way.

Then, in the more distant future, there are the other planets. Satellites about them will yield details that will never be obtainable from purely earth-based observations. An intriguing problem is afforded by the fact that the apparent oblateness of Mars as observed optically differs markedly from the oblateness as determined from mechanical considerations. One may expect still other interesting gravitational problems to turn up as satellites are employed to investigate the planets.

When instrumented capsules, or observatories, can be landed on the planets, geophysical exploration of them can begin--to be consummated perhaps by the landing of human explorers in the course of time. Experience on our own earth, plus experience gained from both manned and unmanned exploration of the moon, will contribute to the success of later planetary ventures. The exploration of the moon, of course, is brought to focus in the Apollo Project.

PLANETARY ATMOSPHERES

Knowledge about the earth's atmosphere has been tremendously extended by means of sounding rockets and scientific satellites, including the TIROS meteorological satellite. Spatial and temporal variations in pressure, density, temperature, composition, motions, ionization, radiations, energy influx and efflux, have all been measured by means of rocket techniques. Here again, it is easy to predict that continued studies of the earth's atmosphere will continue to produce important and sometimes surprising results.

But the new harvest in the study of planetary atmospheres will come from the application to the other planets of techniques that have been so well developed for earth. Already some beginnings have been made in the case of Venus. Mariner II measured surface and cloud top temperatures, which have also been measured in part from the ground. In addition, some indication of temperature variations across the planetary disc were obtained. But almost the full task remains yet to be done. What are the clouds of Venus? What is the composition of her atmosphere? What are the spatial and temporal variations of atmospheric parameters throughout the Venus atmosphere?

What will comparative studies of the Venus atmosphere with that of the earth show about their origins and evolution? What about the Venus ionosphere, and auroral and airflow activity? It has been suggested by a number of people that the bistatic radar technique offers much promise in the study of Venus. That is, with an illuminating radio antenna on the earth and a receiver in the satellite about the planet, considerable information can be obtained about the planet's atmosphere, and especially its ionosphere.

As the most likely planet to harbor extraterrestrial life, Mars' atmosphere is of especial interest. As in the case of Venus, the composition of the atmosphere is an important question to resolve. The white caps observed on the poles are presumed to be very thin layers of frost. If this assumption is correct, then there is water on Mars. The question then arises as to how much water exists in the atmosphere. Measurements made from the vicinity of earth still leave much to be desired, and there are those who flatly contest the validity of any of the answers given so far. The correct answer most likely will come from balloon observations in the years immediately ahead.

A haze that inhibits observation of Mars at the blue end of the spectrum is generally present. Occasionally this haze lifts briefly in what is referred to as the "blue clearing." What causes this haze is certainly intriguing, and may be important, in the study of the red planet.

Again, a comparison of the Mars atmosphere with those of Venus and the Earth should be valuable in studying the origin and evolution of planetary atmospheres.

In the more distant future of the space program there lies the possibility of investigating the major planets, such as Jupiter and Saturn. Jupiter is likely to be the first to receive attention, because it is the nearest. But it is also probably the most interesting. Totally unlike Venus, Earth, and Mars, Jupiter consists largely of hydrogen, helium, ammonia, and methane. Temperatures below the outer atmosphere are presumed to be very cold, so that the main constituents, although normally gaseous, are solid. Yet some of the radiations from the Jupiter atmosphere which include thermal, lightning burst, and synchrotron types, appear to correspond to high temperatures of thousands or tens of thousands of degrees.

The source regions of these high temperature radiations doubtless lie in the upper Jupiter atmosphere. What is the true nature of these radiations? How are they generated? What is the energy source? Enormous energies are sometimes involved. It has been stated that Jupiter is one of the strongest sources of radio waves in the heavens, and that the intensity of the storms which generate the radiation are equivalent to the repeated explosion of a one megaton hydrogen bomb every second.

A perennial source of interest and puzzlement is the giant red spot, varying in size, but roughly 15 thousand kilometers across. What is its origin, the nature?

The very different nature of the Jupiter atmosphere may well require quite different techniques for study from those used in investigating the Earth, Venus, and Mars. Even if the same techniques prove fruitful, the answers are certainly going to be quite different.

INTERPLANETARY SPACE

One of the most exciting products of the early years of the space program has been the investigation of the earth's magnetosphere and interplanetary space. Both have been found to be markedly influenced by solar activity, and a study of them has necessarily required a thorough investigation of the emission of charged particles and magnetic fields from the sun. With the appearance of the satellite and the deep-space probe the subject has virtually exploded with new information and food for thought. You will hear about some of these results from speakers to follow.

We now know that interplanetary space, at least in the region between Venus and Mars, is filled with a wind of particles blowing outward from the sun, with energies characteristically in the several hundred electron volt range. The steady state value of the interplanetary magnetic field appears to be very low, characteristically a few gamma. Solar activity constantly modifies this interplanetary medium, by injecting into it high energy particles and magnetic tongues, which disturbances in the case of solar flares can assume vast dimensions before they dissipate.

The solar wind distorts the earth's magnetic field by compressing it on the side toward the sun and extending it by a factor of two or more in the anti-solar direction. Flare particles and fields give rise to marked disturbances in the magnetosphere which are also associated with considerable disturbances in the earth's atmosphere and ionosphere.

Yet, in spite of the many advances that have been made, there is still a long road to travel before our understanding of the interplanetary medium is in a staisfactory state. For as far into the future as we can now see the road ahead is paved with more questions than answers. We have still to pin down the directionality of the interplanetary field, and its spatial and temporal changes associated with solar activity. Even today, the question as to exactly how solar energy carried by solar particles and fields is injected into the earth's magnetosphere is unresolved. What, for example, is the role of hydromagnetic waves in this process?

We have yet to complete a survey of the magnetosphere, which clearly plays a fascinating role in the solar terrestrial relationships. A study of the interplanetary space in the vicinity of the earth over a complete solar cycle is yet to be carried out. Nor are we yet able to send our instruments close enough to the sun to investigate solar particles and fields in the vicinity of their origin, where we may find clues as to how they acquire their great energies and how they are ejected from the sun. Some theorists estimate that we must come well within a solar radius of the surface of the sun to begin to pry open the secrets of the solar flare process.

Looking the other way, we may well ask where is the boundary between the interplanetary and the interstellar media? Or indeed, is there any marked boundary between the two? Perhaps the interplanetary medium merges into the interstellar. If there is such a boundary, is it within a few astronomical units of the sun, or many tens of astronomical units? How does its position vary throughout the solar cycle?

And what about the other planets? What kind of magnetospheres do they have? Already we know, from Mariner II, that Venus may have at most a weak magnetosphere. As a consequence, the influence of the solar wind and interplanetary magnetic shock waves on the Venus atmosphere must be quite different both quantitatively and qualitatively from their influence on the earth's atmosphere.

LIFE IN SPACE

Certainly one of the most exciting possibilities in space exploration is that indigenous life may be found there. Mars is the most likely candidate. Balloon observations in the infrared have detected emission bands characteristic of the carbon-hydrogen bond. Such emissions may, of course, come from the non-living materials. On the other hand, they may come from biological molecules, which is a highly provocative thought.

The possibility of finding life elsewhere in the solar system is so important to the study of biology that we must be very careful about the course of our exploration of Mars. Steps must be taken to protect the planet from undesirable contamination before we have been able to take advantage of the opportunity to investigate any life that may exist there.

Should life be found on Mars, it is quite likely to be fundamentally similar to that on earth. Nevertheless, it may be sufficiently different to provide, by comparison, extremely illuminating information about the nature of physical life.

ASTRONOMY

The study of the moon and planets might properly be included in the subject of astronomy. So also might be the study of comets, cometary atmospheres, asteroids, and other bodies of the solar system. Many of these investigations of an astronomical nature will doubtless yield very exciting and far reaching results. Nevertheless, the greatest astronomical events in the future will probably come from the investigation of the sun and stars in those wavelengths that cannot be observed from the ground.

Both solar and astronomical satellite observatories are being constructed to take advantage of these exciting opportunities, and as you will hear in the program of this conference, results have already been obtained from the first solar observatory.

These observatories afford man the ability to make observations in ultraviolet, X-ray, gamma ray, infrared, and radio wavelengths that have hitherto been inaccessible to the astronomer on the ground. Theory shows that some of the most important fundamental information on stars lies in these wavelengths. For example, the greatest source of information on stellar birth and evolution lies in the ultraviolet portion of the stellar spectrum. In this very connection, one may refer to results of the Goddard Space Flight Center which have shown that ultraviolet intensities of very hot stars observed from sounding rockets depart very greatly from what had been predicted.

CONTROLLED EXPERIMENTS IN SPACE

Although much of the space science program involves observation of naturally occurring space phenomena, nevertheless, there is now the possibility for the scientist to perform experiments on at least an interplanetary scale. It is quite likely that such experiments will become a significant part of the space science program as the future unfolds.

Experiments to study the nature of gravitation and relativity most readily come to mind. A number of researchers are already thinking seriously of the possibilities of using gravitational clocks, in which the timekeeping element is a dense orbiting satellite, to compare gravitational and nuclear time, and to search for long-term changes in the value of the Newtonian gravitational constant.

CONCLUSION

By way of recapitulation, the most significant result of our current activities in space will be the establishment of our capability to operate and function in space, with such flexibility that we may determine our own destiny in space. This will permit us to select from a wide range of exciting possibilities what we do next in space. Among these choices are many that come under the heading of space science. The investigation of the earth and its gravitational field leads on naturally to the investigation of that of the moon and planets. The study of the earth's atmosphere lays the groundwork for future study of planetary atmospheres and for intercomparisons among them.

The investigation of the earth's magnetosphere and interplanetary space develops quite naturally in at least three different ways. First, one is led in toward the sun to the vicinity of its surface; secondly, out from the sun toward the interstellar medium; and, thirdly, one is led to the study of the magnetospheres of other planets and their relationship to the sun and the interplanetary medium. Life in space may prove to be one of the most important aspects of space science philosophically, particularly if extraterrestrial life is discovered. Among the most exciting opportunities are those found in astronomy, where the range of wavelengths accessible to observation is extended by the satellite to include gamma rays, X-rays, ultraviolet light, infrared and radio waves that do not reach the earth's surface. Finally, controlled experiments in space to shed further light on the fundamental nature of the universe are now possible, the results of which could conceivably lead to entirely new concepts.

VELOCITY DEPENDENCE AND SOURCE SPECTRA

OF SOLAR PROTON EVENTS

BY

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VELOCITY DEPENDENCE AND SOURCE SPECTRA

OF SOLAR PROTON EVENTS

by

Frank B. McDonald

It has become clear from recent satellite measurements[1,2] that solar protons can be transported from the sun to the earth in three distinct ways in addition to the direct way sometimes observed with cosmic-ray monitors at sea level[3]. We wish to describe these four modes of propagation and then show how the velocity dependence of one of these modes makes it possible to determine the energy spectrum of the particles at the time of release from the sun.

We classify solar particle events consisting of radiation with energy above 1 Mev into four distinct classes. The distinction between the classes depends upon the way in which the particles are transported from the sun to the region of the earth. The first two classes consist of particles that arrive at the earth in a manner determined by particle velocity; the first class consists of predominantly higher-energy anisotropic particles that arrive after nearly a direct transit and the second class consists of those that arrive after a diffusive propagation; the third class consists of those that arrive in a manner determined by the motion of enhanced solar plasma; the fourth class consists of those that depend upon the rotation of the sun.

Typical delays between the occurrence of a solar flare and the arrival at the earth of particles in these four classes are different. The delay of the first class event is close to the rectilinear transit time for highly relativistic particles and is therefore only a few minutes. The arrival-time delay of the second class depends upon the rate at which particles propagate through interplanetary space and so varies with energy up to a number of hours. The typical delay for particles in the third class is not a function of energy since particles of all energies arrive with the enhanced solar plasma responsible for Forbush decreases and geomagnetic storms; it is the transit time of solar plasma across one astronomical unit, that is, about two days. The fourth class event takes place near the time of central-meridian passage of a plage region responsible for a flare and solar particle events of the other classes during the previous solar rotation. This fourth class is closely associated with long-lived solar streams. The delay between the parent flare and the arrival of these particles is not a function of energy since particles of all energy arrive with the plasma stream. The delay depends upon the solar longitude of the parent flare and may therefore be as long as one solar rotation, or 27 days. Figure 1 shows the times of occurrence of events of the latter three classes seen by Explorers XII and XIV during parts of 1961 and 1962. Four sequences of events are evident. No events of the first class were seen with sea-level monitors during these time intervals. Figure 2 shows the variation in intensity of interplanetary protons of energy greater than 3 Mev during a sequence involving all the three classes of events seen. Superimposed on the intensity decay of the velocity-ordered event of 28 September is the plasma-associated event of 30 September, followed in turn after 27 event-free days by a recurrent event on 27 October.

We now confine our attention to several velocity-ordered events observed on Explorers XII and XIV. We show how it has been possible in these events to determine separately the influence of the propagation medium and the form of the energy spectrum of particles released from the sun, that is, the source spectrum. These deductions were made possible by the fact that differential energy measurements could be made outside the magnetosphere with the quipment carried by these satellites.

A striking velocity dependence was shown by the solar proton event of 28 September 1961. This is shown by Figures 3 and 4. Figure 3 shows intensity vs. time profiles for various differential energy components. The abscissa is in units of hours from the time of the flare. Figure 4 shows the behavior of the intensities of the same differential components of the event but this time plotted not as a function of time but as a function of distance travelled. The distance travelled is simply the product of particle velocity and time from the flare. The intensity curves of the various components have been vertically scaled to give the best fit to a common curve. The physical meaning of this normalization will be examined further below. We note from Figure 4 that all components lie very closely on a common curve. We may interpret Figure 4 as a measure of the probability that a particle should travel a given distance before reaching the earth from the sun. The fact that we have essentially a common curve shows that particles of all energies travelled a given path length with equal probability. This is true for all path lengths to the extent that the various components of Figure 4 lie on a common curve. The statistical distribution of path length travelled is clearly a property of the propagation medium of interplanetary space. We note that the distance travelled by most particles is an order of magnitude larger than one astronomical unit. This indicates that propagation involved an important degree of scattering. Further, the degree of scattering is not a function of energy over the range examined. This suggests that the mode of propagation is a diffusion-like process and that energy-dependent processes, such as drift across magnetic field lines, do not play a dominant role. In fact, the equation for simple diffusion fits the propagation curve of this particular event through its maximum. It does not fit, though, at the beginning where anisotropy is dominant and at the end where boundary conditions must be taken into account.

Some of the other solar proton events we have observed with Explorers XII and XIV show the same degree of good fit to common, velocity-compensated, intensity vs. distance curves, but a few contrast by not fitting at all. We believe that these exceptions do not weaken our argument for velocity dependence but strengthen it by illustrating that there are times when the properties of the propagation medium cannot, by this technique, be sorted from the source characteristics because, for example, the medium could be changing as the particles are propagating through it. In fact, some solar events may thereby be combinations of events of our first three categories. Although our observations indicate that solar proton intensities in some cases depend very closely upon the first power of velocity, a choice between velocity and rigidity dependence cannot be made from these data alone. There are indications from earlier emulsion measurements of solar proton and alpha intensities[4], however, that velocity dependence is preferable.

We discuss now the physical meaning of the scaling factors used to construct Figure 4. Let us consider the relative intensity of two components of the event. We have recorded the intensities not as a function of time but as a function of distance travelled and found that the ratio of intensities is essentially constant over a range from 2 astronomical units to more than 100 astronomical units. There is nothing to suggest that an extrapolation back to zero distance is invalid. The ratio of the intensities of two components at zero distance is, by definition, a measure of the shape of the source spectrum. Figure 5 shows the source spectrum obtained directly from the scaling factors used to produce Figure 4. The source spectra of two other events analyzed in a similar way are also shown. The ordinate of Figure 5 is arbitrarily chosen to be the maximum intensity reached at the earth. The differential intensities shown are proportional to the absolute differential intensities of protons produced at the sun and retain, therefore, the same spectral form, but the constant of proportionality depends on the geometry of propagation, which is unknown. (For example, since simple diffusion theory fits this propagation curve through maximum intensity, the numerical solution it gives for the source intensity is of the same spectral form, but that solution is for diffusion in an infinite, isotropic sphere, and is probably not a meaningful one.)

We note from Figure 5 that the source spectra are commonly very well represented by power laws in kinetic energy. This fact prompts us to put forward the argument, based purely on aesthetic grounds, that the amount of matter traversed by the solar protons after acceleration was less than the range of 1 Mev proton, that is, about 1 milligram cm^{-2}. It seems highly unlikely that an excess production of lower-energy protons would so exactly compensate their absorption in an amount of material greater than their range such as to produce so simple a form of source spectrum.

An interesting feature of these events is the existence of small-scale deviations from a common curve. Superimposed on the generally velocity-dependent intensity-time profiles are fluctuations which are nearly periodic with the same frequency and phase over the entire energy range studied. These fluctuations are evident in the velocity-ordered events discussed above, but are more striking in the 10 September 1961 event which showed no velocity dependence and was no doubt influenced by greater interplanetary disorder. Figure 6 shows plots of some sample intensities and indicates the periodic fluctuations. In this event the period is about 1.5 hours; in other events the period is slightly different. Since the transit-time dispersion over the energy range studied is significant, the fact, that in any given event, the fluctuations have the same period and are in phase at all energies shows that their origin is local. We suggest, therefore, that they reflect the magnetic field structure in local interplanetary space, but we as yet have no explanation for their periodicity.

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D. A. Bryant, T. L. Cline, U. D. Desai and F. B. McDonald,
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R. A. R. Palmeira and K. G. McCracken,
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4. Hydrogen, Helium and Heavy Nuclei from the Solar Event on November 15, 1960,
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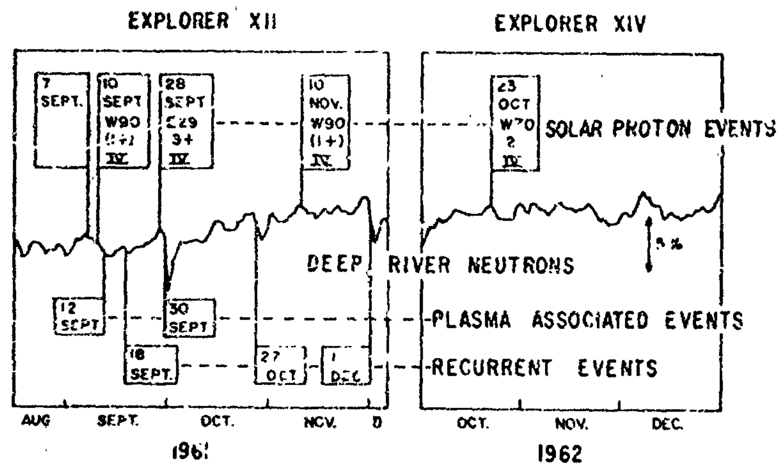

Figure 1

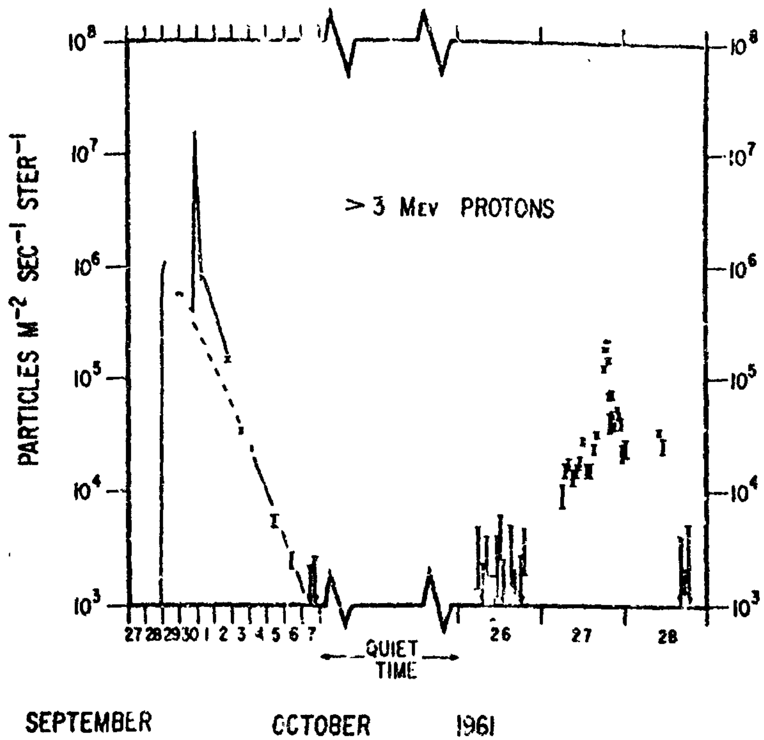

Figure 2

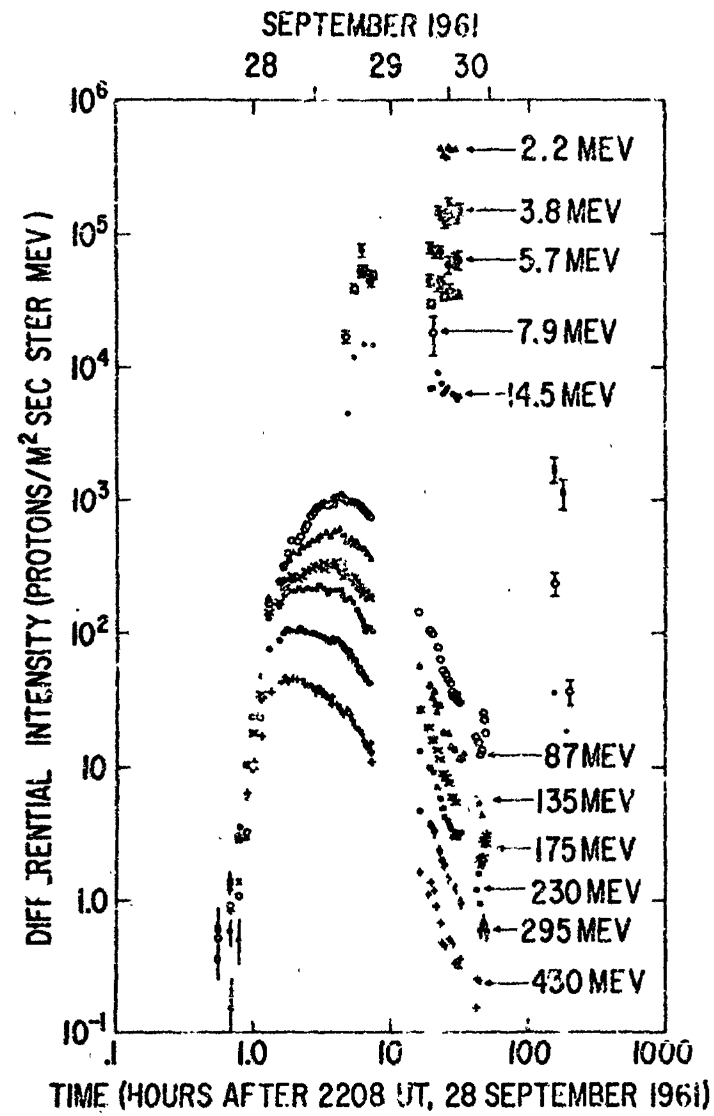

Figure 3

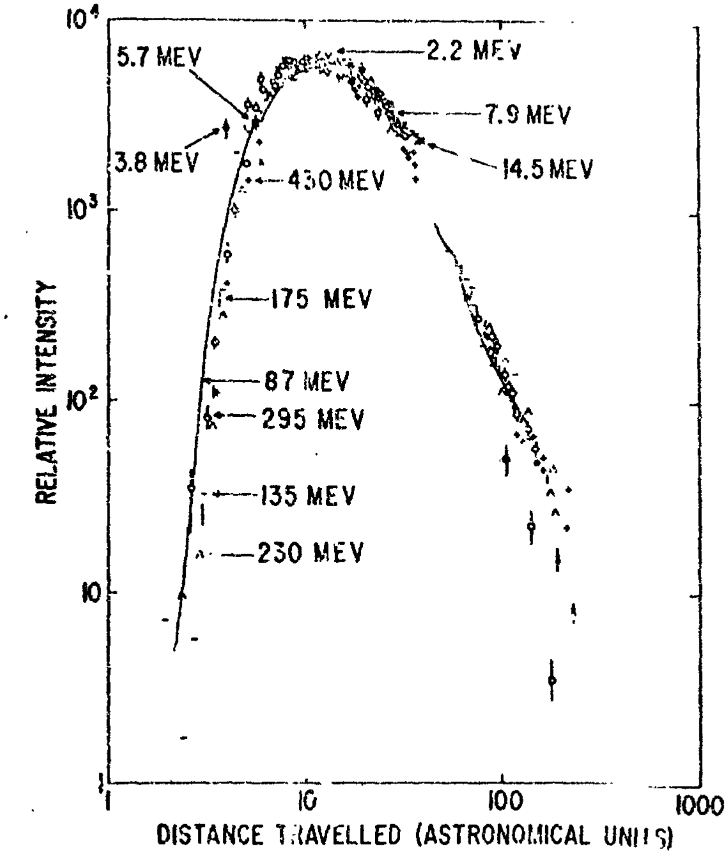

Figure 4

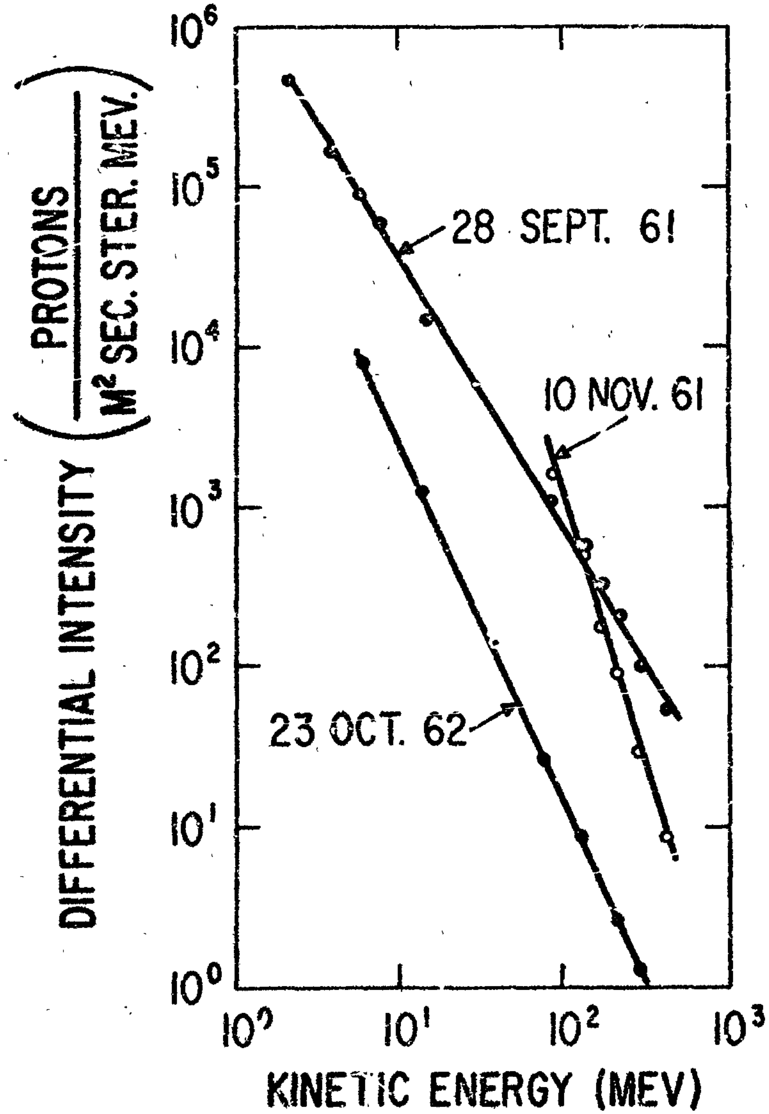

Figure 5

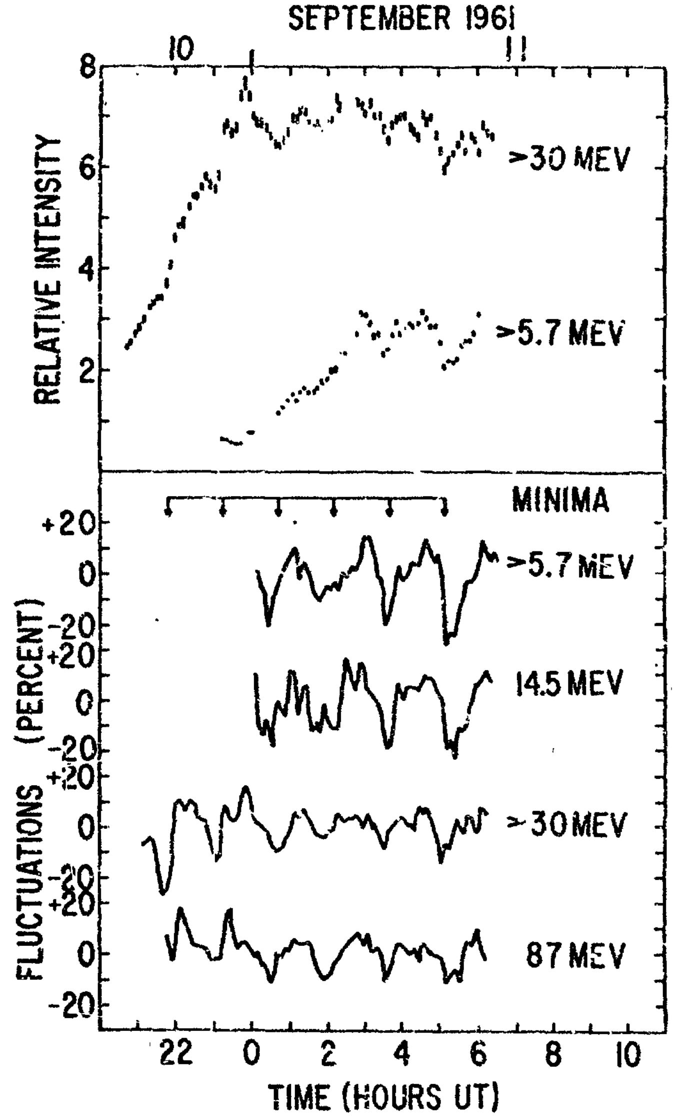

Figure 6

GEODETIC INFORMATION AND IMPLICATIONS

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G ODETIC INFORMATION AND IMPLICATIONS

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Since 1958 a series of measurements has been made on the earth's gravitational field by the aid of artificial satellites. The earliest papers in these series, apart from the very preliminary announcement by L. Jacchia in March of 1958, was the nearly simultaneous announcement i the Summer of 1958 of the earth's flattening by Diercks et. al., at Army Map, Cornford in England, and Buchar in Czechoslovakia. These announcements were collected by Newell and Cormier (1960). The work has been brought to fruition by the efforts of D. G. King-Hele in England (1963), Kozai at the Smithsonian Astrophysical Observatory (1962), and especially by my colleague, William Kaula (1963), in the Theoretical Division at the Goddard Space Flight Center. On the first slide we see a presentation of Kaula's results based on a spheroid with a flattening of 1/299.8.

The study of the implications of these new measurements begins with the paper by my colleague, S. W. Henriksen at Army Map. (Newell and Cormier, 1960) Henriksen showed that if the observed value of the flattening of the earth is combined with the measurement of the luni-solar precession then it is possible to calculate the polar moment of inertia of the earth. From the polar moment of inertia it is possible to calculate that value of the flattening which the earth would have if it were in hydrostatic equilibrium. The process is, in fact, rather simple; the standard theories of the flattening of the earth lead directly from the value of the polar moment of inertia to the predicted flattening. The situation has become somewhat confused over the last fifty years because until recently it was not possible to determine the polar moment of inertia in any satisfactory observational way. As a result, it was customary to make the assumption, which until 1958 was quite satisfactory, that the actual value of the flattening coincided with the value predicted from hydrostatic theory, within the errors of observations. If this assumption is made, and if we use the luni-solar precession then we find that the flattening of the earth should be 1/297.3. This value is often incorrectly spoken of as the hydrostatic value of the flattening. It would be such if the earth were in hydrostatic equilibrium with the observed value of the luni-solar precession. The situation is mildly analogous to Whistler's remark that if silicon had been a gas, he would have been a major general.

In fact, the measured flattening of 1/298.24 means that we are not in hydrostatic equilibrium and that the hydrostatic value must be determined directly from the polar moment of inertia. The latter is found observationally from the measured value of the flattening and the observed value of the precession. When this is done we find, as Henriksen pointed out, values near 1/300.0 and, in fact, a value of 1/299.8 seems to be a close approximation. The calculation when made by Henriksen's algorithm is not seriously disturbed by the fact that the earth is not in hydrostatic equilibrium. The failure of the oblateness of the earth to agree with its predicted value by one part in 200 implies a change in the polar moment of inertia by only about one part in 100,000. Thus it is entirely consistent to calculate the hydrostatic value to four significant figures even though we must start from an earth which is slightly out of hydrostatic equilibrium.

We have come to our first geophysical implication, namely, that the equilibrium value of the earth's flattening is near 1/299.8.

Let us now examine the meaning of the depressions and ridges which we see on the map which represents Kaula's work. The largest feature is clearly the difference between the actual flattening and the hydrostatic flattening. The implications of this for the inner constitution of the earth have been studied by Munk and MacDonald who conclude that it is apparently due to a slowing down of a rotation of the earth. Recently, direct evidence of the slowing down of the rotation has been obtained.
The point is that the less rapid rotation demanded a lesser flattening; but the earth has not quite kept up with this change. This implies that the earth has sufficient internal mechanical strength to maintain a non-equilibrium figure over a considerable length of time (some 50 million years, according to G. J. F. MacDonald (1960)). The only alternative to the idea that the earth possesses the necessary mechanical strength is the hypothesis that these irregularities in figure are supported somehow by convection currents. The convection current explanation is especially unacceptable for the second harmonic because it would be expected on general physical grounds that a second harmonic convection current would be weaker than the corresponding third harmonic. In fact, it would be very difficult to start convection currents corresponding to a second harmonic in the mantle because of their shallowness as compared with their great size. Other explanations may be offered for this second harmonic, but in a brief speech of this kind it is not possible to develop them fully.

What can be said with assurance is that this harmonic is no temporary feature of the earth's surface. It corresponds to elevations and depressions of hundreds of meters in the sea level surface. Moreover, since the disturbances of the terrain which are required to produce a given alteration of the sea level surface are larger by a factor of two or more than the changes of the sea level surface itself, it would require movements of many hundreds of meters in the land surface to remove them. On the other hand, the most rapid known movements are at the rate of about ten centimeters per century. These are far from coordinated; hence the deformations which we are speaking of must have been in existence for hundreds of thousands of years at least. They are irreconcilable in particular with the picture of plastic deformation which are presented by Heiskanen and Vening Meinesz (1958), p. 369. According to these authors a second harmonic deformation should collapse in a thousand years.

Neither is it reasonable to think of these deformations as resulting in some way from the solidification of the earth from a liquid body. Solidification would presumably have occurred in a spherically symmetrical way. There might conceivably have been perturbations due to ellipticity but there should not have been perturbations which depend on longitude. In some way or other these irregularities must result from the action of mechanical forces on the interior of the earth, and very likely from forces acting after the earth had formed its core, since the plasticity required for the formation of the core seems inconsistent with the mechanical strength here involved.

If we trace the history of the earth-moon system backward in time then the laws of celestial mechanics tell us that the moon steadily approaches the earth. At the same time the earth's rate of rotation becomes faster as we go back. We have suggested that the non-equilibrium value of the flattening was a survivor of the time when the earth rotated more rapidly. Can we go back in imagination to a still more remote time and attempt to explain the other harmonics?

It turns out that if the earth once revolved once in about 3 hours, it tended to develop an ellipsoidal shape which not only possessed a flattening but for which, in addition, the equator was out of round. Such a figure is spoken of as triaxial; three unequal axes could be constructed in the body. Two of these would be in the plane of the equator while the third and shortest would be the polar axis. This problem was extensively treated by many celestial mechanicans from the time of Jacobi, who discussed this curious behavior of a rotating fluid through Poincare, G. H. Darwin, Liapounov and in our time, Lyttleton.

In Darwin's time it was felt very difficult to understand the origin of the moon because he believed that the interactions in the earth-moon system would transfer angular momentum from one body to another but could not export or import angular momentum with respect to the system as a whole. There are, it is true, solar tides but the action of these is much smaller than that of a lunar tide. Darwin (1898) calculated their effect and showed that it was utterly insufficient to change the system as a whole. In more recent times, however, it has been repeatedly pointed out that angular momentum may be transferred by the interaction between the gravitational field of the earth and that of the surrounding medium or the plasma in the surrounding medium. A somewhat naive approach to the problem is presented by R. H. Wilson (1956). Wilson was arguing on the analogy of the retarding forces expected on the Vanguard satellite by the earth's magnetic field. He forgot that in a large solid body like the earth, currents will be induced which will prevent the magnetic field from penetrating into the interior of the earth. The process is something like the skin effect in which rapidly alternating currents are confined to the surface of a conductor. The diurnal change of the magnetic field which would be produced by a conducting earth rotating in a planetary magnetic field is a slow alternation by human standards but a very quick alternation by comparison with the earth's self-induction. As a result the effect of an external gravitational field on the earth is much less than a naive theory would suggest. It is probably insufficient to retard the earth seriously.

At a time when the earth was more disturbed than now, it is conceivable that the rotation might have been retarded by the expulsion of plasma from the ionosphere. The plasma which is ejected this way will tend to rotate with the same angular velocity as the earth as long as it is in the earth's magnetic field. This property of co-rotation means that as the plasma gets further from the earth it takes up a disproportionate amount of the earth's angular momentum. When it is finally released it has slightly retarded the earth's motion. Present day plasmas in the neighborhood of the earth are apparently far too tenuous to have much effect this way. One can calculate tha if this angular velocity were fed into the whole amount of the solar wind as it passed the earth for four and a half billion years the net effect on the angular momentum would still be entirely negligible. On the other hand in ancient times both the sun's magnetic field and the earth's magnetic field and the plasmas may have been and very likely were much more substantial phenomena. The question is one which many physicists are now studying and I think it is legitimate to hope that a solution will be found and for our purposes to put this problem aside.

A most interesting question which can be asked at this time point is what triggered the separation of the moon from the earth? Since the moon has a density like the mantle of the earth it is logical to assume that it separated from the earth after the formation of the earth's core. Is this possible?

There are several difficulties involved in the idea of the fission of the earth. These have been most clearly brought out by Lyttleton (1953). Lyttleton aimed most of his fire at the notion that double stars could have been produced by the fission of single bodies. This idea is no longer entertained by anyone; we all agree that the stars are gaseous in nature and this in turn implies that rotational breakup of stars will take place by the ejection of matter from the equator in a thin ring, rather than by division into two bodies as Jeans (1919) pointed out. Lyttleton also pointed out that division into two nearly equal bodies is impossible, at least in the case of homogeneous bodies, because the angular momentum of the resulting pair of objects would exceed that of the initial one. This difficulty holds unless the ratio of the masses of the bodies is more than three to one. The difficulty does not persist however for much smaller bodies.

A third problem which Lyttleton saw arose from the fact that the angular velocity of rotation of the single body is greater than that of a pair of bodies in the closest possible proximity to each other. He concluded that if a small body should escape from the main one it would leave the whole system permanently and would escape to infinity. However, between these two extremes, namely, the infinitesimal bit which escapes to infinity and the even division into two parts which haven't enough angular momentum to make a clear separation, we can reasonably expect that there will be a place for fission into two fragments which orbit about one another in the manner considered by Darwin.

In his long study of this problem Jeans pointed out that the stellar case, namely that of bodies which will break up by the ejection of a ring of matter, is approached by bodies whose central mass condensation is very great. That is to say, the lighter the matter is on the outside compared to the core, the less the tendency is to divide into two bodies. This is logical: If a rapidly rotating planet should reach the point where part of its atmosphere spilled out into space we wouldn't expect to see it ball up into a compact mass and go off making like another planet; but if the spilled outer part is dense then its self attraction will be strong and any lump which forms on it will attract other matter and tend to grow until eventually it detaches itself.

Now the question is, whether the outer part of the earth is sufficiently dense so that it would detach itself as a lump or not? Jeans has given a measure of this tendency in terms of the so-called polytropic index. The polytropic index, n, is related to the ratio of specific heats (heat at constant pressure divided by heat at constant volume) which would exist in an imaginary gas convecting and having the observed density distribution. In fact, $n = \frac{1}{\gamma - 1}$. For our purposes we may say that it is an arbitrary parameter measuring the degree of central condensation. Jeans has demonstrated that if γ is more than about 2.2, i.e. the polytropic index less than 0.8, the body will break up by fission into two parts, but if it is greater than 2.2, the body will break up by equatorial ejection of matter. What polytropic index should we take for the earth?

Perhaps the most logical way to calculate the polytropic index, that is the effective concentration to the center, is to calculate the earth's moment of inertia and find out what polytropic index would give the moment of inertia. We find, by numerical integration in Emden's table that the moment of inertia of the earth corresponds to that of a body whose polytropic index is slightly less than 0.5. It follows that it is on the side of the homogeneous bodies and will break up, if at all, by fission. Clearly this point deserves further investigation.

We come back to the initial question, will the formation of the core help or hinder the process of breakup? On the one hand the formation of the core will reduce the moment of inertia of the earth. Heavy material moves in toward the center of the earth as the core if formed and it displaces lighter material outward so that the net effect is a reduction in moment of inertia. Since the angular momentum which is conserved is the product of the moment of inertia by the angular velocity, it follows that the angular velocity must increase, and this of itself would tend to destabilize the earth, making it liable to fission. On the other hand, the mere concentration of mass to the center asserts a stabilizing effect particularly against the formation of a Jacobi ellipsoid as we saw before. Which of these two tendencies will win out?

It turns out when we calculate using the results of Jeans for an earth whose density varies according to the law $\rho = \rho_0 - kr^2$ that the earth is in fact destabilized by the formation of the core. For this reason we can imagine that the earth was at first a very rapidly rotating homogeneous mass. In this mass the cooling which resulted as the early radioactivity decayed, permitted a separation of the iron from the stone and hence the formation of the core. Up to this point the earth had been stable, though perhaps only barely stable, but with the formation of the core a Jacobi ellipsoid was produced which extended itself and eventually tore apart to form the earth and the moon.

Just prior to the destruction of the Jacobi ellipsoid the earth's mass must have undergone a redistribution in which portions moved outward in preparation for the splitting off. At this time the moment of inertia of the earth must have increased and hence its angular velocity must have decreased. The process is similar to that which is used to reduce the angular velocity of a spinning satellite by releasing a portion of it. As a consequence, the moon, when released from the earth, may have been travelling with a velocity less than the velocity of escape and so may have been retained in orbit around the earth.

At this time the moon and the earth each raised very large tides in the other. However, as the earth shrank back toward a less extended mass its angular velocity tended to increase. At first, its velocity of rotation and the moon's velocity of revolution coincided. If at this time the moon was in an eccentric orbit, then the moon ran ahead of the tidal bulge on the earth when the moon was near its perigee and ran behind the tidal bulge in the outer portion of its orbit near apogee. As a result, the moon was retarded near perigee and accelerated near apogee. Darwin has shown that the result of these two actions is to diminish the eccentricity of the moon's orbit. Qualitatively, the argument is clear enough. If the body is retarded when near perigee this will tend to lower the apogee, as in the familiar case of a satellite in a decaying orbit. The acceleration at apogee on the other hand tends to increase all of the orbit except the apogee portion, which clearly cannot change because the action of a force is to cause a change of velocity but not an instantaneous change of position. Thus the apogee acceleration tends to raise the perigee and the perigee retardation to lower the apogee and both to reduce the eccentricity. The orbit thus becomes progressively more and more round and retreats steadily from the earth, as Darwin pointed out long ago, owing to the lags produced by tidal friction. There is a critical distance beyond which the effect of tidal friction is to increase rather than to decrease the eccentricity. Since the moon is well outside that distance its eccentricity is now probably increasing and has been increasing for a long time.

A difficulty which is often brought up against the fission theory of the origin of the moon is based on the concept of the Roche limit. This concept asserts that a satellite which has the temerity to venture within approximately 2 1/2 radii of the primary will be torn apart by tidal friction. This is true for a very small satellite, but for a larger one there is an influence of the mutual gravitational attraction which serves to stabilize the situation. The tides raised in the primary, especially if it is rotating rapidly, attract the matter of the secondary particle toward a particular longitude in the orbit and in this way preserve it against the shear actions which would otherwise tear it apart. The matter has been very carefully gone into by both Darwin and Jeans; there can be no doubt that when the primary and secondary corotate it is possible for them to be very close without destruction of the secondary.

In tracing the further history of the moon we should note first the remark of Öpik (1961) that the moon does not have regions in which the craters are systematically distorted. It follows that the crust which we are now looking at must have been formed after the moon reached what is substantially its present distance. In fact, Öpik says the present surface of the moon was produced after the moon had got to a distance of more than 30,000 kilometers from the center of the earth.

The remark is comforting since it indicates that some action perhaps of a volcanic nature refashioned the moon's surface after it had got to a substantial distance. This agrees with the indications that we get from the hypothesis that tektites are from the moon. If this idea is right, there have been large eruptions of volcanic materials during the last few hundred million years. The tektites indicate that the moon's surface which we now see is not at all a primeval surface.

May I close by saying that these remarks cannot claim to be an established theory. They may, however, serve to illuminate paths along which further research can profitably be conducted.

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THE EARTH'S ATMOSPHERE - DENSITY

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15494

Summary

After an introductory review of the entire atmosphere, this paper discusses air density and its variations at heights of 200-2000 km, as revealed by analysis of satellite orbits and by other methods. The atmospheric density at these heights varies greatly in response to solar activity: at 600 km height the density decreased by a factor of 30 between 1958 (sunspot maximum) and 1962 (near minimum). Density also varies strongly between day and night, the maximum daytime value exceeding the minimum nighttime value by a factor of up to 10 at some heights.

Author

1. Introductory

The atmosphere used to be looked upon as a thin shell of air clinging to the Earth on its journey through the 'perfect and absolute blank' of interplanetary space, and it was thought that artificial satellites, if they ever became reality, would move 'outside the atmosphere'. In fact, the coming of satellites has enormously enhanced the prestige and importance of the atmosphere, by showing first that it extends out to 10 or 15 Earth radii, and second that at its outer boundary it is being battered by the hail of charged particles which constitute the Sun's atmosphere.

Thus, instead of looking on the atmosphere as a thin and trivial covering of the Earth, we can rather regard the Earth as a small nucleus in the vast volume of the atmosphere,

This island in the ocean of the air,

to adapt a line of Shelley's. And the atmosphere's continual struggle against particles from the Sun at its outer boundary is a drama which engages our interest, because it is a battle to shield us from the lethal effects of solar particles; when the Sun breaches the boundary, the atmosphere shows it has been wounded by putting on a display of the aurora (though not all aurorae are red!).

2. A general picture of the atmosphere

Any attempt to draw a diagram of the entire atmosphere is perhaps rather foolish, because it is bound to provoke disagreement: nevertheless Fig. 1 is such a diagram, and it must be emphasized that it represents only the average conditions, for average solar activity (sunspot number $\simeq$ 60), averaged between day and night, etc. Fig. 1 should therefore be regarded more as a visual aid than an exact specification.

It is best to consider first the air temperature, shown towards the left of Fig. 1, since the temperature does give some indication of the heights at which solar energy is absorbed. On climbing from sea level into the troposphere, the temperature falls fairly steadily to about 210°K at a height of roughly 10 km, then remains nearly constant in the stratosphere, up to a height of about 25 km. Above that comes a rise in temperature caused largely by ozone absorbing solar ultra-violet light: the amount of ozone is very small - only about one part in 100,000 of the atmosphere at these heights - but very important; for it not only determines the air temperature but also shields us from the harmful solar ultra-violet radiation. So we find the temperature rising to a maximum of about 280°K at a height of about 50 km. Then temperature falls, because of heat loss due to long-wave radiation from molecules of ozone and carbon dioxide, and reaches a minimum of about 180°K at a height of about 80 km. The region from 25 to 80 km is often but not always called the <u>mesosphere</u>.

Above 80 km the temperature starts increasing again and goes on doing so up to about 300 or 400 km; above that the temperature is independent of height up to the height where it ceases to be properly definable, somewhere between 1000 and 2000 km. For average solar activity, the temperature in this region, from 300-400 km upwards, is about 1000°K, as shown in Fig. 1; but at sunspot maximum, temperature can be as high as 2000°K by day and at sunspot minimum is probably about 700°K by night.

The terminology for these regions is unsatisfactory. The term thermosphere is often used for heights from 80 up to about 800 km. Above that, the mean free path of the neutral molecules becomes so large that they ought to be treated like miniature ballistic missiles, and the term exosphere is often used. (There are signs however that the term thermosphere is often reserved for the region of increasing temperature, up to about 300 or 400 km.)

In the lower thermosphere the electron density reaches two peaks, first in the E layer at about 100 km, and then in the F region, which in daytime shows two maxima at heights of about 180 and 300 km. In radio parlance these particular regions used to be called the ionosphere; but in fact the proportion of ions and electrons is only about 1 in 1000 at 300 km, and goes on increasing above 300 km. The term ionosphere is probably best avoided altogether when discussing the atmosphere in general, because it refers to particular components, the ions and electrons, and not to any particular height-band.

At heights of 1000-2000 km the neutral molecules are more numerous than the ions. Above 2000 km, however, the charged particles gradually become dominant, and, since their behaviour is governed primarily by the Earth's magnetic field rather than the gravitational field, it is useful to recognize a new and outermost region of the atmosphere called the magnetosphere. Most of the charged particles in this region have ordinary thermal energies, but there are also the zones of high-energy charged particles, both natural and artificial.

When the Sun is quiet, the outer boundary of the magnetosphere occurs at between 9 and 15 Earth radii (heights of 50,000 - 90,000 km), on the sunlit side of the Earth. The continued outflow of charged particles from the Sun, the 'solar wind', compresses the Earth's magnetic field on the sunlit side, and draws it out on the dark side, so that the magnetosphere is not really spherical but pear-shaped[1]. The boundary, which on the sunlit side is a hydromagnetic shock wave in the supersonic flow of the solar wind, continually fluctuates, and the boundary is completely breached when violent disturbances occur on the Sun. Much more intense streams of particles then reach the Earth's vicinity and break through almost to the surface.

Though we have now reached the end of the Earth's atmosphere it is worth remembering, as indicated in Fig. 1, that the Earth's gravitational sphere of influence relative to the Sun extends out to about 900,000 km, well beyond the Moon's orbit.

The main components of the atmosphere are indicated on the left of Fig. 1, the chief component being given first in each of the groups of components. Up to 80 km the sea-level composition is maintained; as height increases from 80 to 200 km more oxygen is dissociated into atomic form, but the molecular weight (29 at sea level) is still about 25 at 200 km. As height increases from 200 to 600 km, atomic oxygen becomes predominant, and the molecular weight falls to about 16. Then comes a region where helium is predominant: the thickness of this region varies greatly with solar activity, day/night changes, etc; for the average conditions of Fig 1, it is from about 700 to 2000 km. Above this, hydrogen is dominant, with an increasing proportion ionized.

Thus we have a gradual decrease in molecular weight: the numerical values depend on solar activity, but for the average conditions of Fig. 1, molecular weight decreases from 29 at sea level, to 16 at about 600 km, to about 4 at 1500 km and not much more than 1 at 3000 km, thus confirming the naive picture of the lighter gases rising to the greater heights,

> Where lighter gases, circumfused on high,
> Form the vast concave of exterior sky.

as Erasmus Darwin put it, 175 years ago.

Finally, on the left-hand side of Fig. 1, there is the number of molecules per c.c., 2.5×10^{19} at sea level, decreasing to about 10^{10} at 200 km, 10^{4} at 2000 km, and perhaps about 10 in the Sun's atmosphere.

It is interesting that in our modern picture of the atmosphere we have really gone back to the sixteenth-century picture, which in turn derives from Aristotle. The sixteenth-century picture was of a 'Sphere of Air' round the Earth, which in its upper reaches was very hot because it was in contact with the 'Sphere of Fire' (or the Sun's atmosphere, as we might now say). These ancient speculations have proved more accurate than the science of 40 years ago, according to which the upper atmosphere was very cold, and all was blank beyond.

3. Determination of air density from analysis of satellite orbits

The rest of this paper will be mainly concerned with air density and its variations at heights of 200-2000 km. Most of the information on this topic has come from analysis of satellite orbits and the methods used will now be briefly described.

A satellite moving in an elliptic orbit suffers the greatest air drag when it comes nearest to the Earth, at perigee. Thus the effect of air drag is to retard the satellite as it passes the region of perigee. Consequently on the next revolution it does not swing out so far on the opposite side of the Earth: the apogee height is reduced while the perigee height remains almost constant, and the orbit contracts and becomes more nearly circular, as shown in Fig. 2.

The rate at which the orbit contracts, or the rate at which the orbital period T decreases,* is therefore a measure of the air density at heights near that of perigee: if the orbit, mass, shape and size of the satellite are known, a value for the air density can be obtained. It is assumed that the drag D of a satellite moving with velocity v can be expressed as

$$D = \frac{1}{2} \rho V^2 SC_D$$

where ρ is the density of the ambient air, C_D is a drag coefficient which may usually be taken[2] as 2.2 for heights of 200-600 km, and S is the satellite's mean cross-sectional area perpendicular to the direction of motion. It is customary to assume also that density varies with height y according to the equation

$$\rho = \rho_p \exp \left\{ -1 \ (y-y_p)/H \right\}$$

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* The orbital period is the most convenient parameter to use, because it is easily determined. Two naked-eye visual observations a day apart can give T correct to 1 part in 20,000, and better observations give correspondingly better accuracy.

where suffix p denotes values at perigee and H, a quantity which is a measure of the density gradient and is known as the 'density scale height', is assumed to vary linearly with height. Under these assumptions, for orbits with eccentricity e between about 0.02 and 0.2, the density ρ_A at a height $\frac{1}{2}H_p$ above perigee height can be expressed in terms of $\dot{T}$, the rate of change of T, by the equation[3]

$$\rho_A = - \frac{0.157\ \dot{T}}{\delta} \quad \frac{e}{aH_p}\left[1 - 2e + \frac{5}{2}e^2 - \frac{H_p}{8ae}\left(1-10e + \frac{7H_p}{16ae}\right)\right]$$

where $\delta = FSC_D/m$, m is the mass of the satellite, F is a factor (lying between 0.9 and 1.1) which allows for the rotation of the atmosphere[4], and a is the semi major axis. Formulae are also available[3-5] for other ranges of values of e, and an additional term can be added to take account of the oblateness of the atmosphere[6]. The great advantage of this equation is that is is very insensitive to errors in the value chosen for H_p, which is not known exactly: a 25% error in H_p leads to an error of only about 1% in ρ_A.

Alternatively, though at the expense of a much greater amount of computation, air density can be evaluated by numerical integration of the drag round the orbit, assuming some model atmosphere. Again, to minimize the effects of errors in the model, the value quoted for ρ should be at a height of $\frac{1}{2}H_p$ above perigee.

With the aid of these methods a complete picture has now been obtained of the density of the neutral atmosphere and its variations at heights of 200-800 km, together with a good indication of the variations at heights up to 2000 km. Heights above 2000 km can be regarded primarily as the realm of the charged particles and will not be discussed further here.

4. The main variations in upper-atmosphere density

The density of the atmosphere at heights above 200 km has proved to be very strongly under solar control, in two quite distinct ways: first, it responds to the presence or absence of solar radiation, the day-to-night effect; second, it responds to solar activity, density (and temperature) being greater when the Sun is more active. The day-to-night effect is best described first, because it is more regular and provides the basic model on which the other variations are superposed.

4.1. The day-to-night effect

It is found that at heights of 200-800 km the density of the atmosphere increases during the morning and reaches a fairly sharp maximum at about 2 p.m. local time. It then declines fairly steadily until midnight, reaches a flat minimum between midnight and dawn, and begins its morning increase again. The effect is small at 200 km height, but becomes very large at greater heights.

This effect is shown up particularly well by the changes in the orbital period of a satellite, because the perigee point is continually moving under the influence of the Earth's oblateness, and the time it takes to go from day to night and back again is usually between 2 months and a year. This is long enough to give time for the effect to declare itself unmistakably, but not so long that we have to wait a lifetime to see it. Fig. 3 shows the orbital period of Explorer 1 (perigee height 350 km) from February 1958 to January 1963. The curve is marked 'day' when the perigee is in sunlight and 'night' when the perigee is in darkness, and it is apparent that in each day-to-night cycle the slope becomes steeper after day dawns, reaches its steepest somewhat after noon and then becomes less steep as night draws on. Since $\dot{T}$ is proportional to ρ_A, these changes in slope exactly reflect the changes in air density.

At a height of 200 km this day-to-night change in density probably does not exceed $\pm$ 10%, except when sunspot activity is near its minimum, but at greater heights the factor $f = \frac{\text{maximum day-time density}}{\text{minimum night-time density}}$ is sometimes as high as 10. Some typical results, for 1959 and 1962, are shown in Fig. 4. When the Sun is active, as in 1959, the day-to-night change only becomes important above 300 km: at 400 km, f = 1.6; at 600 km, f = 5.5; and at 800 km, f = 10. On the other hand, when the Sun is rather inactive, as in 1962, the day-to-night change becomes important at a lower altitude and its maximum amplitude declines. In 1962, f = 2.5 at 300 km; at 400 km, f = 4; the maximum value, f ~ 5, is attained at about 500 km, and f decreases to 4 again by 600 km.

Fig. 4 incidentally also shows that the decrease in solar activity between 1959 and 1962 brought a great general decrease in density, both by day and by night.

The day-to-night changes in density have so far been described as if they depended solely on the local time, which is merely the difference in longitude between the Sun and the relevant point. This picture, though convenient, is true only in equatorial regions, because the density seems to depend primarily on the altitude of the Sun above the horizon, rather than the local time. The regions of increased density by day seem to show a roughly circular symmetry about a point centered underneath the Sun, or, to be exact, underneath a point about 2 hours or 30^{o} east of the Sun's position. The Sun, as it were, draws up the atmosphere into a bulge underneath, so that the contours of constant density on the sunlit side are much higher - about 100 km higher at a height of 400 km - than on the dark side. For a point at any given latitude the daily variation in density does rise to a maximum at 2 p.m. local time; but the true maximum - the peak of the daytime bulge - is only reached at locations where the Sun is almost overhead. At higher latitudes only the upper slopes of the bulge, rather than its peak, are sampled.

Further details of these variations in density may be found in refs 7 - 9, and their causes will be discussed in section 6. We now go on to describe the other effects.

4.2. The response to solar activity

Although the day-to-night changes in density are extremely large, the changes in response to solar activity are even larger, and were detected first. The early Sputniks had perigee heights near 200 km, where the day-to-night effect was not important, but the rate of change of their orbital periods showed erratic fluctuations which soon came to be correlated with solar activity.

Fig. 5 shows the original results for Sputnik 2: the actual values of T fluctuate about the 'theoretical' curve, which is based on the assumption that the density is constant from day to day. The variation in density deduced from Sputnik 2 is shown in Fig. 6 and compared with the sunspot numbers: there is obviously some resemblance between the two, and one of the characteristic features of solar control, the tendency towards a 27- or 28-day recurrence, is also apparent.

From such beginnings have come a whole series of elegant comparisons between atmospheric densities and indices of solar activity, in which the work of Dr. Jacchia of the Smithsonian Astrophysical Observatory (refs 10-12) deserves a special mention.

What index of solar activity should be used? Some property of the Sun itself, such as sunspot numbers or solar flares, is possible; but even better is an index which measures the effect of the Sun on the Earth. An index which has proved most useful in the solar radiation energy on 10.7-cm wavelength, as received at ground level. This radiation, since it penetrates the atmosphere, can have no direct effect on the upper atmosphere; but it is believed to provide a good indication of the solar ultra-violet radiation, which <u>is</u> absorbed in the upper atmosphere and provides a major source of heating. The variation in atmospheric density often shows a marked resemblance to the variation in the 10.7-cm radiation energy, as we shall see shortly.

The other useful index is the planetary geomagnetic index a_p (3-hourly) or A_p (daily), which indicates the average degree of disturbance in the ground-level terrestrial magnetic field. Most major variations in the magnetic field - the magnetic storms - result from the impact of streams of high-energy particles from the Sun on the magnetosphere. Thus the geomagnetic index provides us with the best indication of solar corpuscular streams encountered by the Earth; although it is an imperfect index, it is more likely to be correlated with upper-atmosphere density than is, say, the record of solar flares, which are highly directional and may not influence the Earth at all.

In considering the response of the atmosphere to solar activity, it is worth distinguishing three different time-scales. First, there are the irregular day-to-day fluctuations, including as spectacular examples the occasions of large magnetic storms. Second, these fluctuations, when plotted out over a long period, often tend to show a 27-day recurrence, because the Sun rotates, relative to the Earth, once every 27 days. Third, there is the slow variation in the course of the 10-year sunspot cycle. Considering the complexity of the phenomena, it is remarkable how well the various effects have been sorted out.

A brilliant example is shown in Fig. 7, which gives Jacchia's results[10] on the air density as revealed by the orbits of 7 satellites at the time of the great magnetic disturbance of mid-November 1960. At all heights from 200 to 1200 km, there is a large transient increase in density - it increases by a factor of 8 at 700 km height; and this increase is exactly in unison with the magnetic disturbance. All the satellites also reflect the second and smaller magnetic disturbance two days after the main one.

The correlation is not always as close as this, and an excellent general picture is given by Fig. 8, which shows the rate of change of orbital period due to air drag[12] for Explorer 9. Almost all the strong magnetic disturbances, the peaks on the lower curve, are paralleled by a corresponding peak on the upper curve. On the other hand, the upper curve is also obviously undergoing variations which have no connexion with the magnetic index. There are, for example, some strong 27-day fluctuations towards the right of the diagram: these are well correlated with 10.7-cm flux.

This is shown in Fig. 9, which includes some of the same data as Fig. 8, and has been marked to indicate the various features already mentioned.

To sum up, the density of the upper atmosphere shows a strong day-to-day correlation with the 10.7-cm radiation and also with geomagnetic disturbances; it is therefore probably influenced both by ultra-violet radiation and by streams of particles from the Sun. On a longer time-scale, the density shows a 27-day recurrence tendency and exhibits a slow and massive change in the course of the sunspot cycle, as Fig. 4 has already partially shown.

Thus, combining the two types of solar control so far discussed, we have a picture of an upper atmosphere which is drawn up into a hump roughly underneath the Sun, and also fluctuates both on the day and night sides in response to solar activity. The density and temperature are higher when the Sun is above the horizon rather than below, and also higher when the Sun is active rather than quiescent.

4.3. The semi-annual and annual variations

The effects already discussed are extremely large, and can lead to changes in density by a factor of 10 or more. The two other effects to be discussed now are much smaller than this, but still quite substantial, amounting to about ± 20% at 400 km.

From the work of Paetzold and others[13-15] it appears that upper-atmosphere density undergoes a semi-annual variation with minima in January and July, and maxima in April and October. Generally, however, the July minimum is deeper than the January one, and the October maximum is higher than the April one. This would imply an annual variation superposed on the semi-annual variation. Paetzold's findings on this point are very clear,[14] as shown in Fig. 10, but other investigators have not obtained such unequivocal results and the annual variation is still slightly controversial.

The semi-annual effect, which has also been noticed in geomagnetism, is probably due to the fact that the Sun emits particles most strongly in some particular plane, probably near the Sun's equator, which the Earth would cross twice a year. The annual effect could be partly due to the annual variation in the Earth's distance from the Sun (as a result of which the solar radiation received on Earth is about 6% less in July than in January), or to the Earth's differing motion with respect to the interstellar medium through which the whole solar system is presumably moving.

5. The variation of density over a sunspot cycle

Fig. 11 shows the air density at heights of 200-800 km, calculated from the observed changes in the orbits of 38 different satellites, over the greater part of a sunspot cycle from 1958 (maximum) to 1962 (near-minimum). The curves shown are maximum daytime and minimum nighttime values.

Several features of Fig. 11 are worth nothing. The Figure indicates that, on taking an average over a solar cycle, the density decreases by a factor of 10 as height increases by about 130 km, for heights of 200-800 km. Fig. 11 also shows how the daytime density decreased between 1958 and 1962, by a factor of 5 at 400 km and a factor of 30 at 600 km. The change in the nighttime density is generally rather smaller, but the greatest possible variation between the daytime density at sunspot maximum and the nighttime density at sunspot minimum is by a factor of more than 100.

6. Mechanism of solar control

It is now well established that the temperature of the upper atmosphere is virtually independent of height at heights from 300-400 km (the exact value depends on solar activity) up to the height where temperature becomes a meaningless concept (somewhere between 1000 and 2000 km).

The temperature can be determined because it is closely related to the air density, the slope of the curves in Fig. 11 being proportional to temperature divided by molecular weight. Alternatively, a model of the upper atmosphere can be devised, such as Nicolet's diffusive-equilibrium model,[16] in which density can be derived from temperature; temperature can then be varied until the density agrees with the observed values. These methods show that the temperature above 300-400 km is 30-35% higher at the daytime maximum than at the nighttime minimum, and that the basic nighttime temperature rises from about 700°K at solar minimum to about 1500°K at a solar maximum as intense as the 1957-8 maximum.[7,11]

Thus the Sun can be regarded as exercising its control over the upper atmosphere by the heating effect of its ultra-violet radiation and the streams of particles - either the quiet flow of 'solar wind' particles or the violent outbursts of particles associated with solar flares. The ultra-violet radiation is absorbed at heights near 200 km, and the influence of heating then spreads upwards. The modus operandi of the charged particles is not yet so clear: probably they interact with the magnetosphere at its outer boundary and generate hydromagnetic waves which dissipate their energy as heat at lower levels. But some of the charged particles may also filter down as high-energy ions via the zones of radiation, and communicate their energy directly.

The composition of the atmosphere above 300 km depends on the prevailing temperature. By day at solar maximum (temperature = 2000°K) atomic oxygen (molecular weight 16) is dominant up to 1500 km. At medium solar activity (1200°K) helium (M.W.4) begins to dominate over atomic oxygen at heights above 700 km. At sunspot minimum by night (700°K), helium becomes dominant even lower (at about 500 km) but is in turn displaced by hydrogen at 700 km.*

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* Since temperature is independent of height, the slope of the curves in Fig. 11 is inversely proportional to the molecular weight, and the increase in the slope of the 1962 curves near 600 km is due to the increased proportion of helium in this year of low solar activity.

7. Conclusion

The density of the atmosphere at heights of 200-1000 km has the following characteristics. At a height of 200 km the density varies comparatively little and never differs from 4×10^{-13} gm/c.c. by a factor of more than 2. At greater heights the density is greater by day than by night, the factor of difference increasing with height until it reaches over 10 at 700 km when the Sun is active; when solar activity is near minimum, the factor of difference does not exceed 5, but the day-to-night effect becomes important at a lower height.

The density shows a close correlation with solar radiation energy and geomagnetic disturbances, and at heights near 600 km can increase for a few hours by a factor of up to 8 in severe magnetic storms. It also tends to exhibit the 27-day recurrence tendency characteristic of solar influence, and undergoes a large variation in the course of the 10-year sunspot cycle, density at sunspot maximum by day being over 100 times greater than at sunspot minimum by night, at heights of 500-700 km. Much smaller semi-annual and probably annual variations occur.

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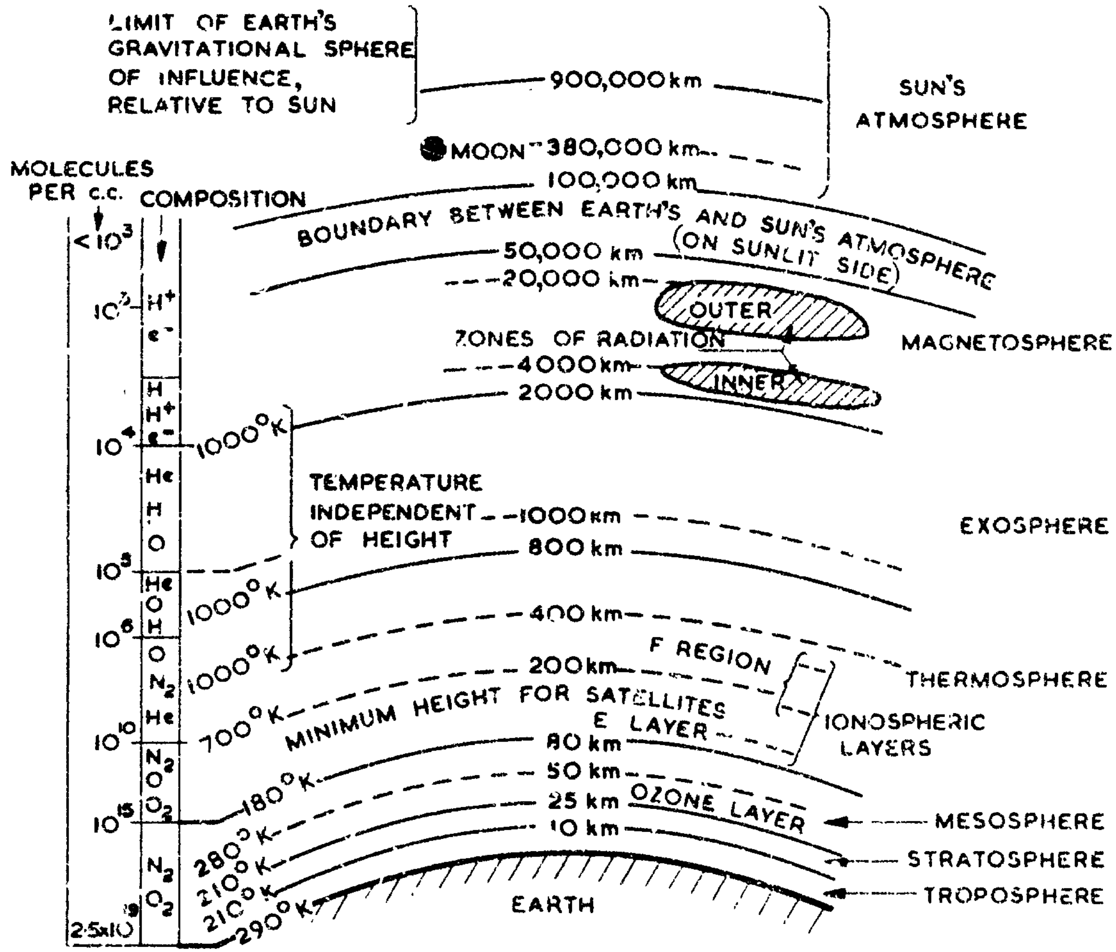

Fig. 1 DIAGRAM OF THE ATMOSPHERE

(NOT TO SCALE. AVERAGE VALUES, FOR AVERAGE SOLAR ACTIVITY.)

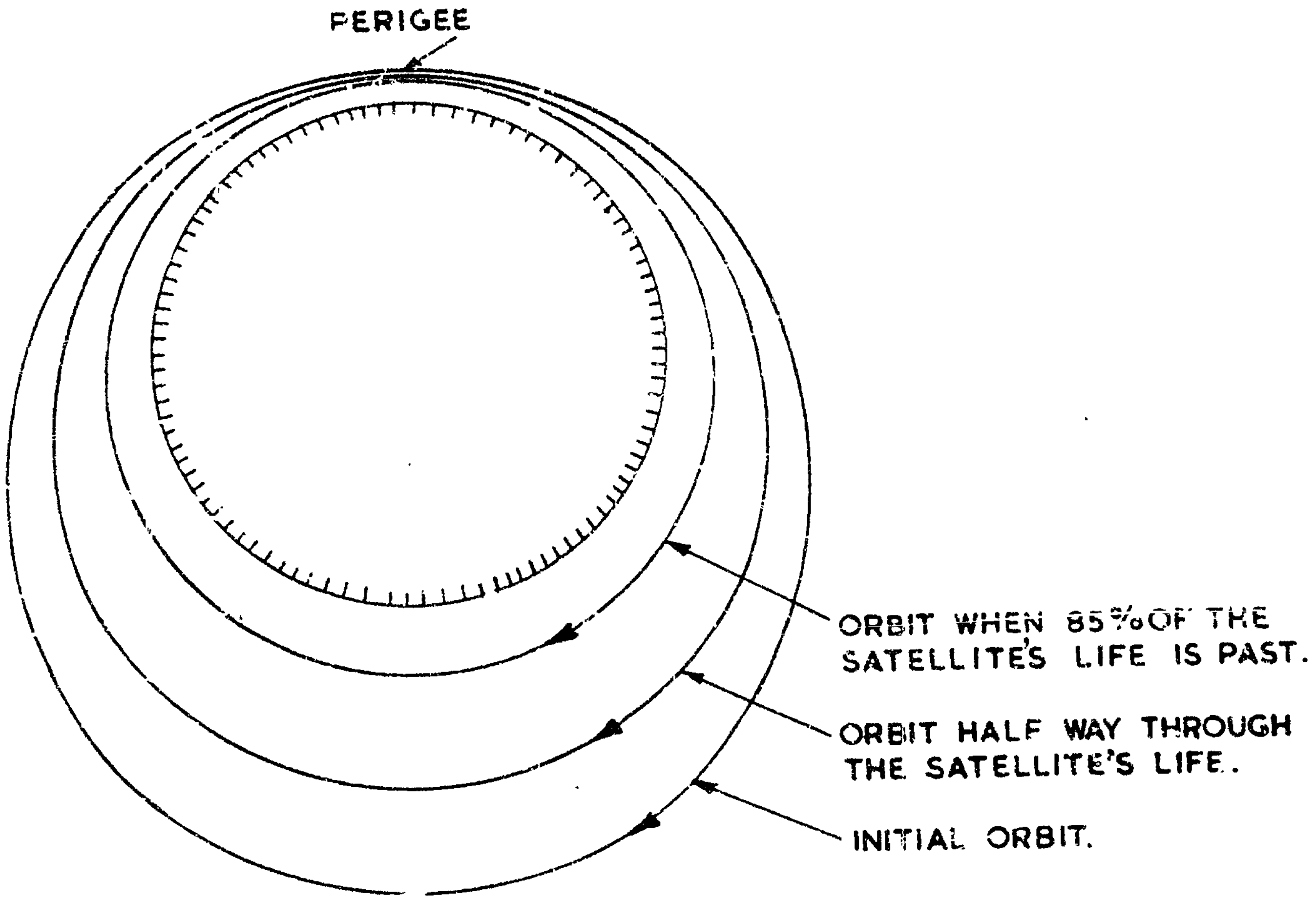

Fig. 2

CONTRACTION OF SATELLITE ORBIT UNDER THE ACTION OF AIR DRAG

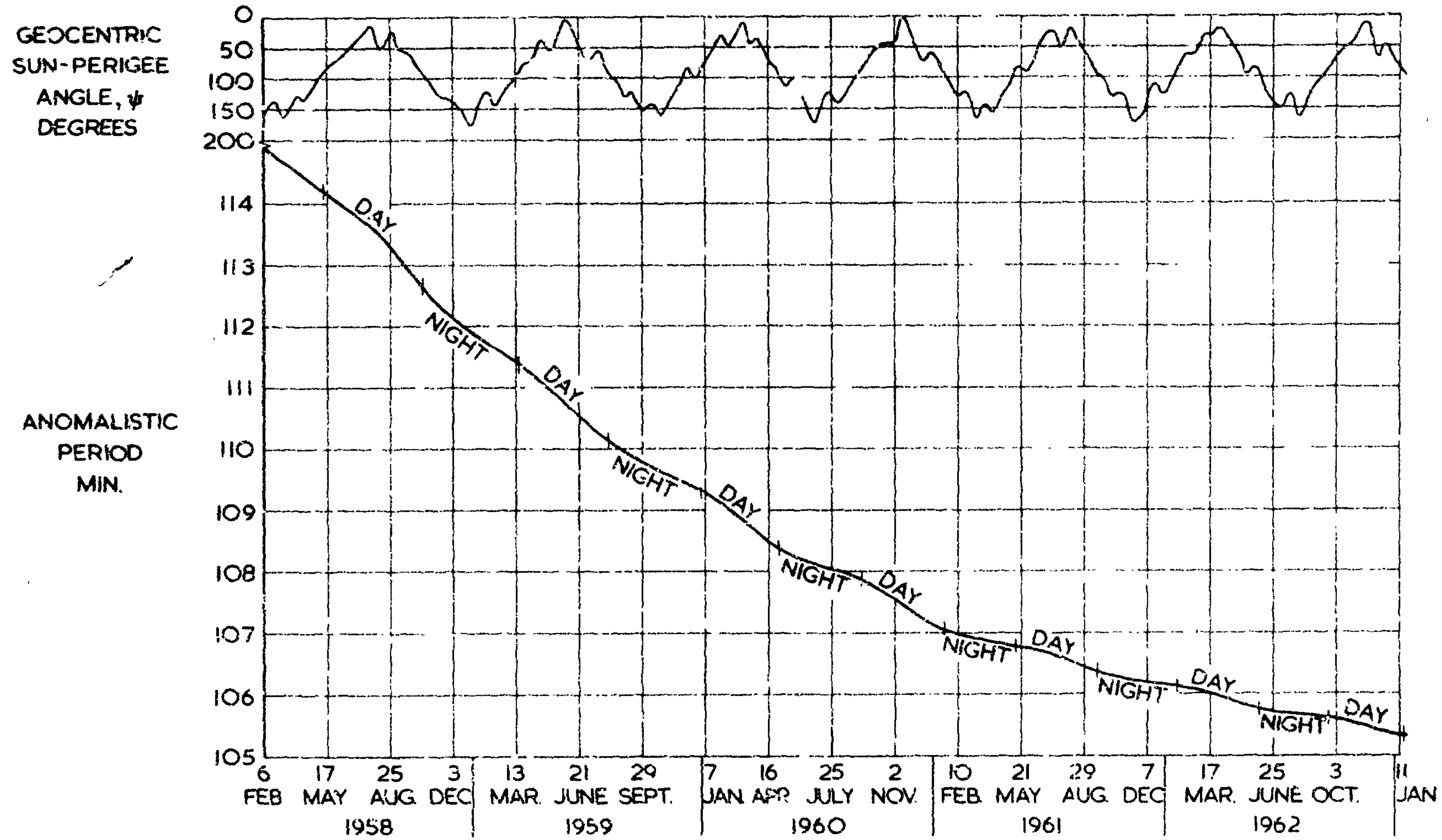

Fig. 3 ORBITAL PERIOD AND GEOCENTRIC SUN - PERIGEE ANGLE FOR EXPLORER I, 1958 α

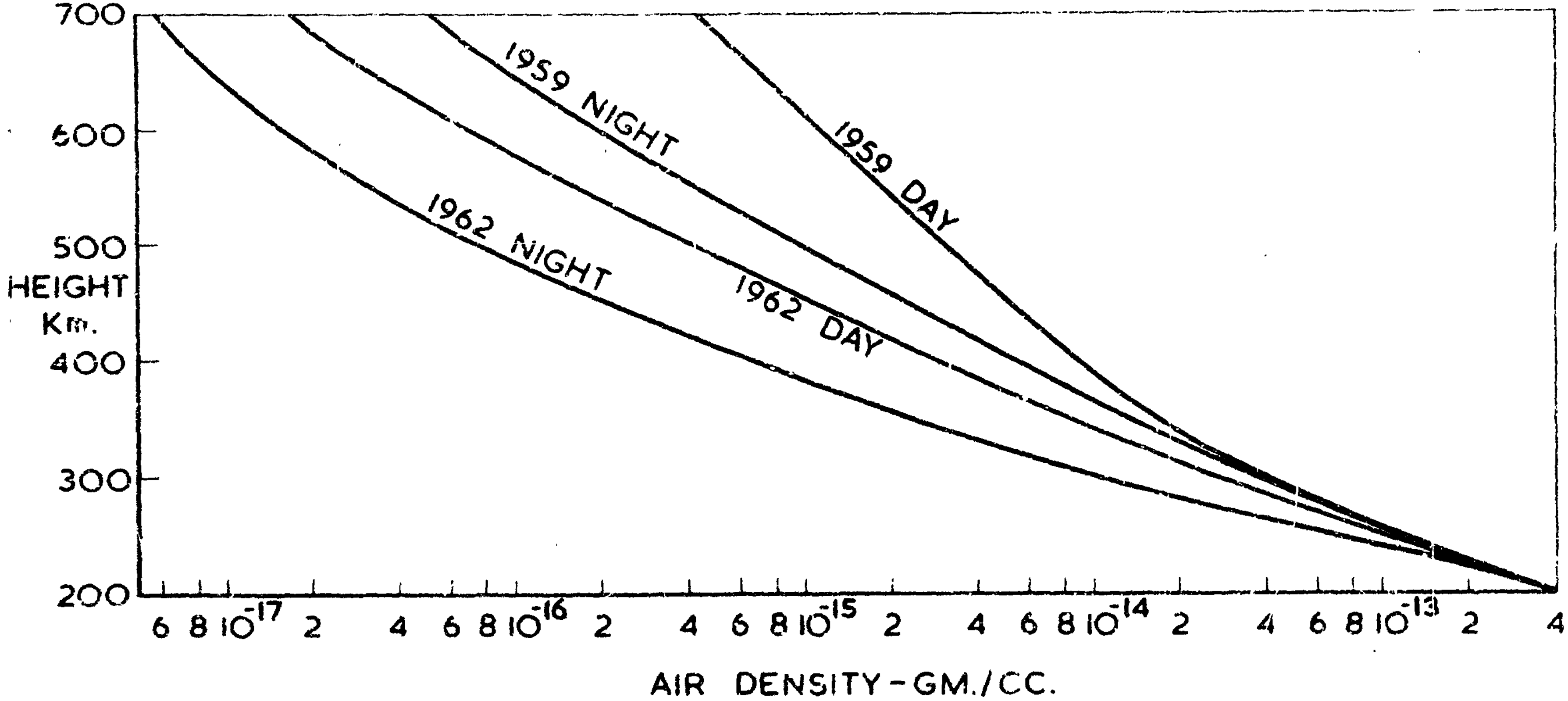

Fig. 4 DAY-TO-NIGHT VARIATION FOR 1959 AND 1962.

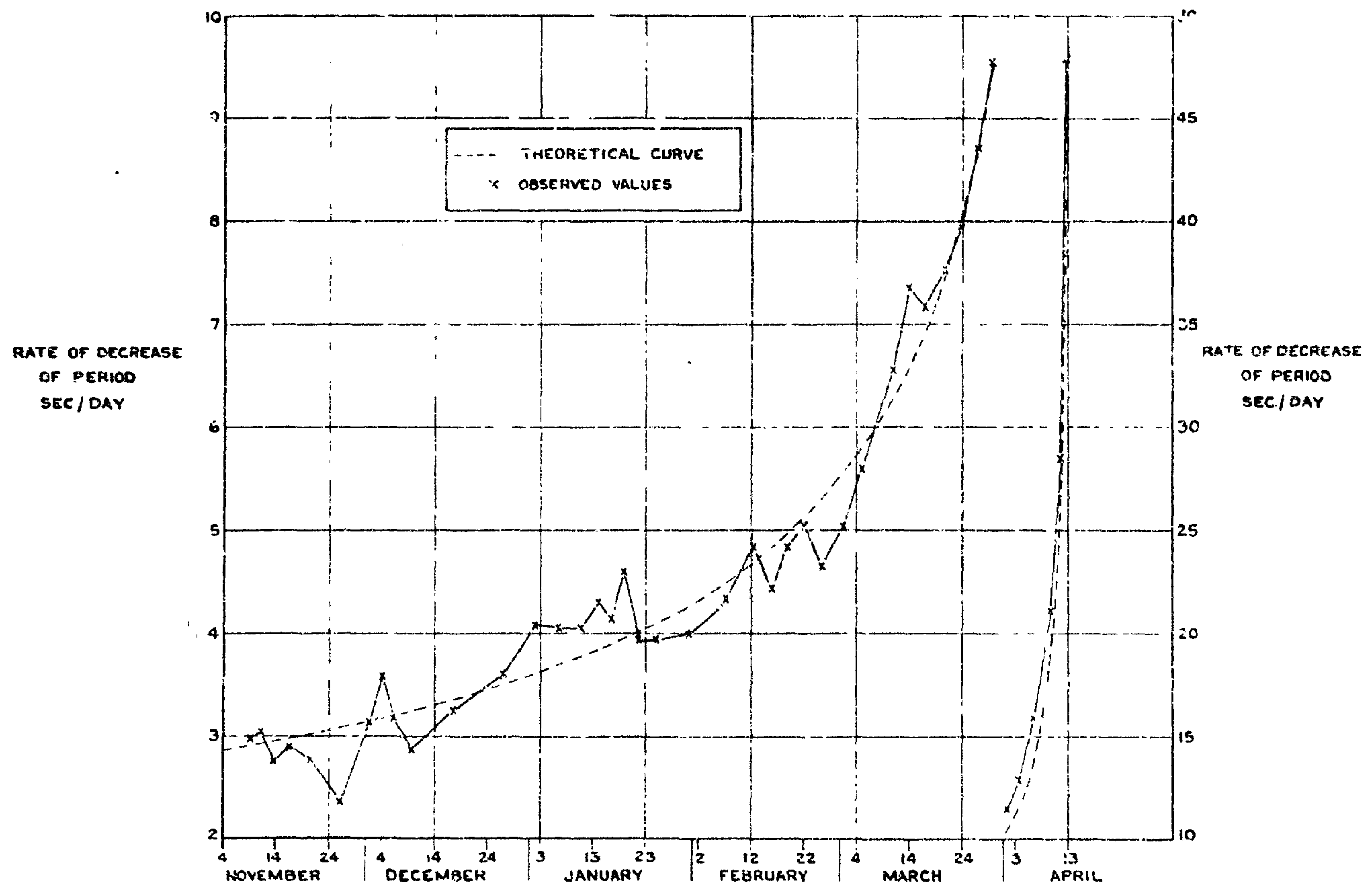

Fig. 5 **RATE OF CHANGE OF PERIOD FOR SPUTNIK 2 (1957β).**

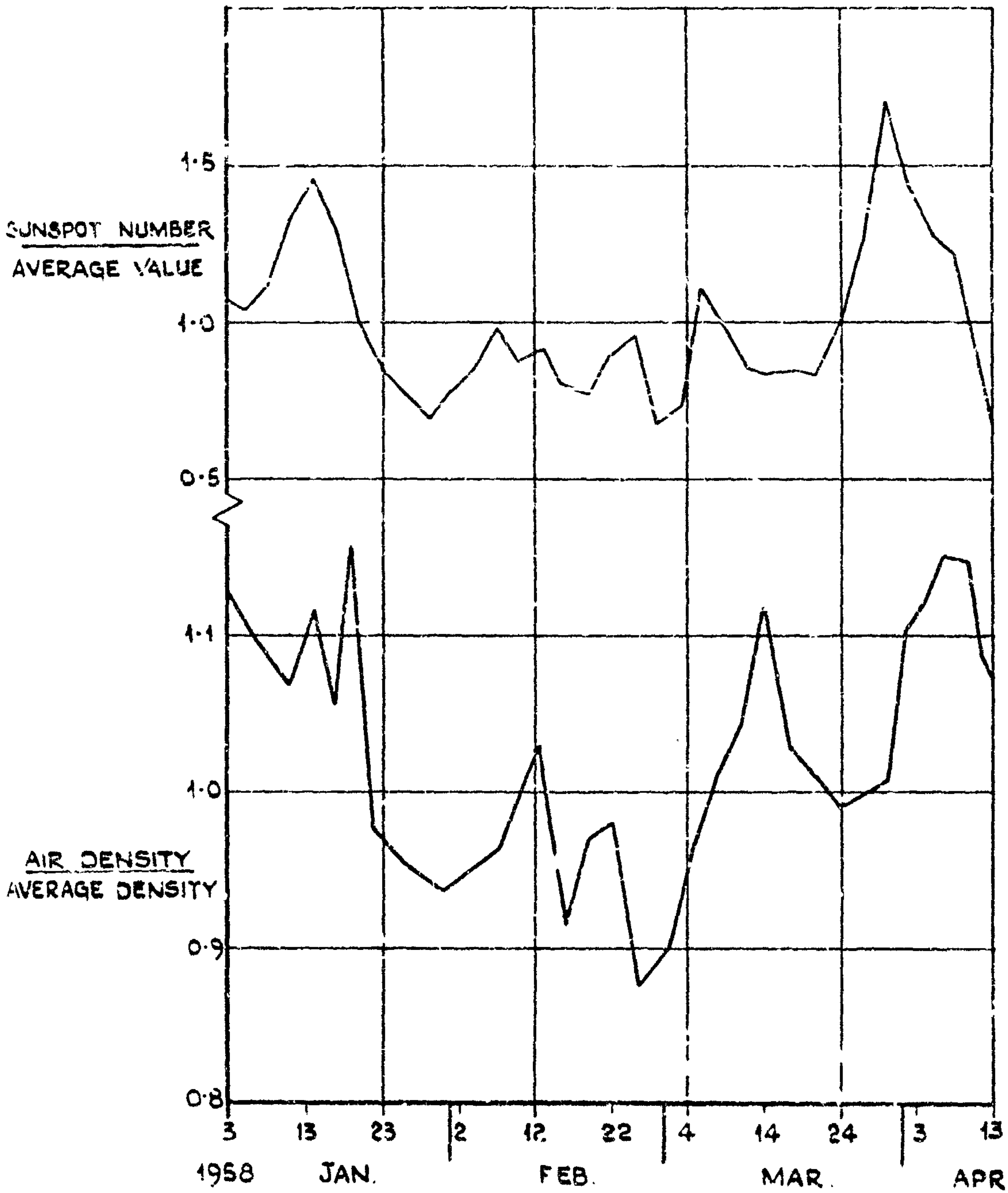

Fig. 6 **COMPARISON OF SUNSPOT NUMBERS WITH DENSITY AS GIVEN BY SPUTNIK 2**

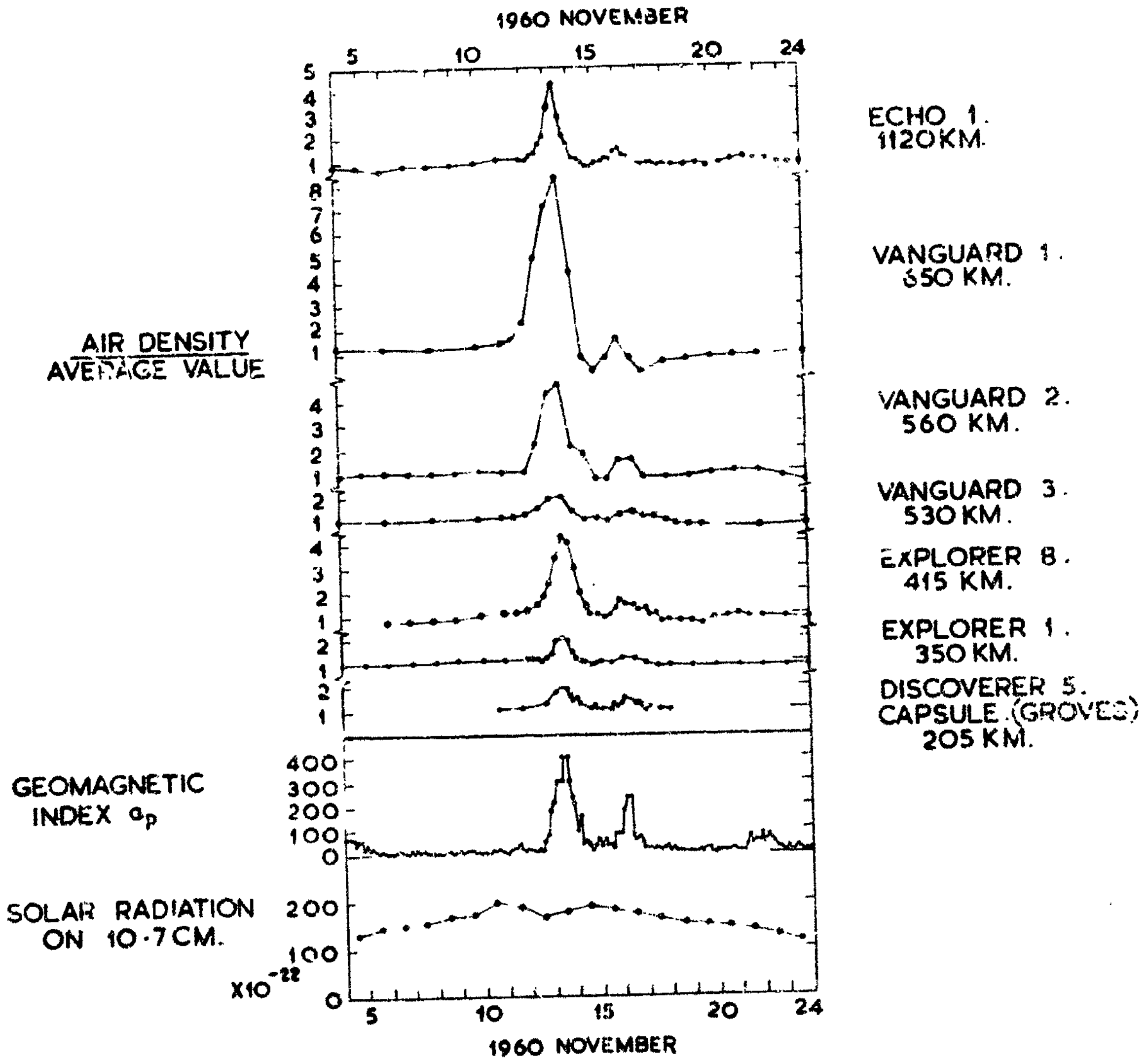

Fig. 7 VARIATION OF AIR DENSITY IN NOVEMBER 1960, AS REVEALED BY 7 SATELLITES. (AFTER JACCHIA, SMITHSONIAN SP. RPT. 62.)

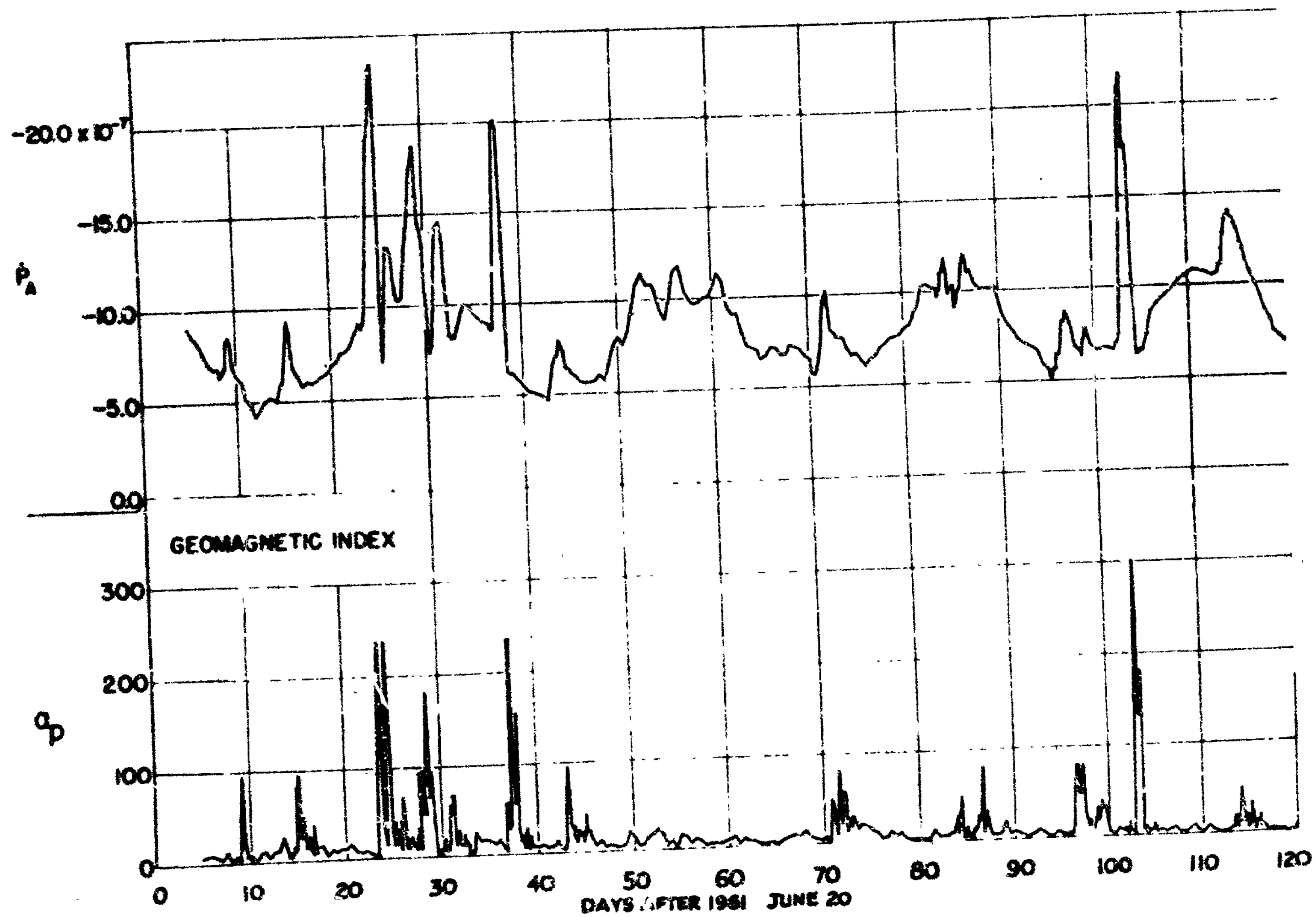

Fig. 8 RATE OF CHANGE OF ORBITAL PERIOD $\dot{P}_A$ DUE TO AIR DRAG, FOR EXPLORER 9, WITH GEOMAGNETIC INDEX a_p

(AFTER JACCHIA, SMITHSONIAN ASTROPHYS. OBS. SP. RPT. 125)

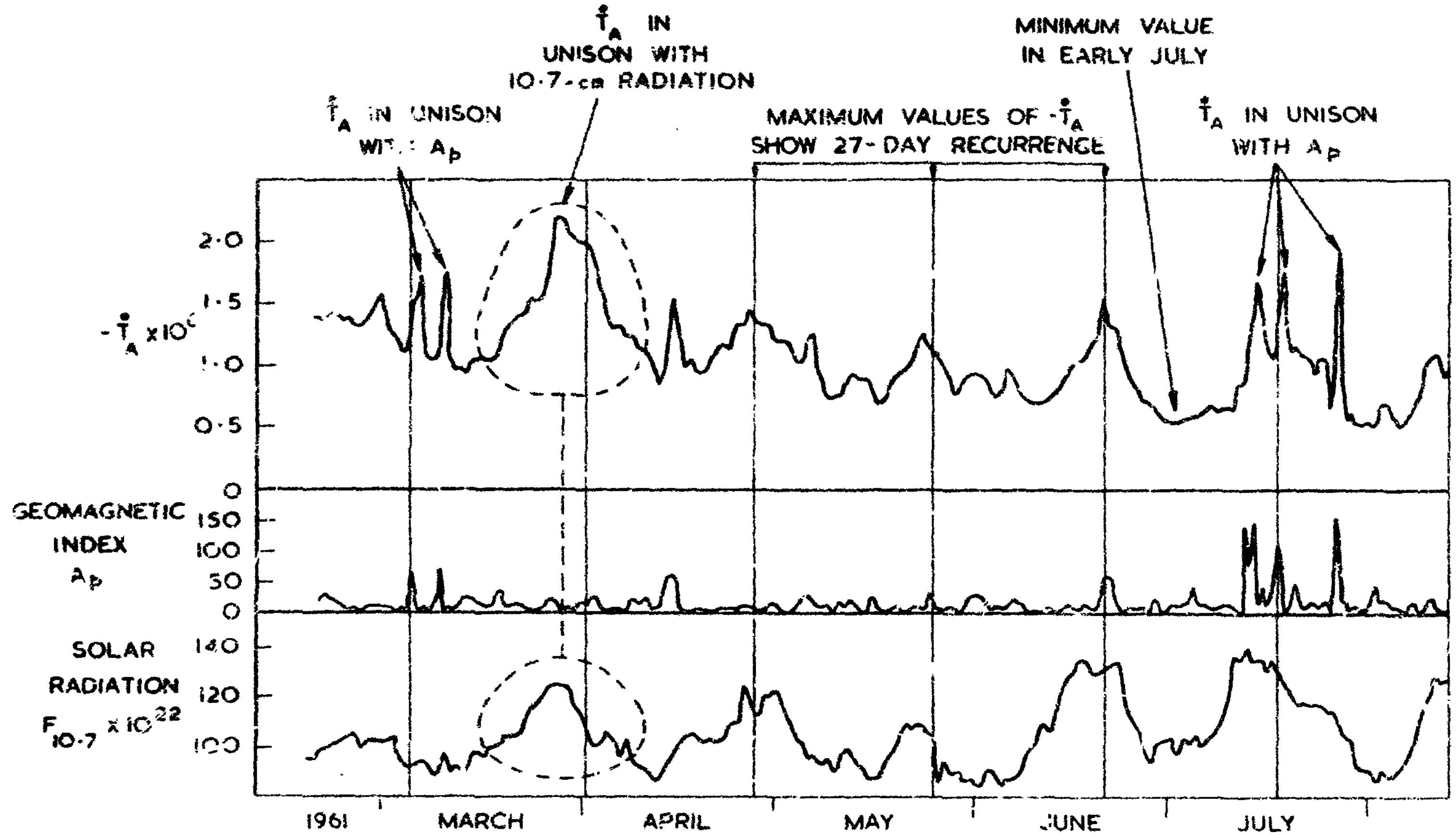

Fig. 9 CHANGE IN ORBITAL PERIOD DUE TO AIR DRAG, $\dot{T}_A$, FOR EXPLORER 9.

(AFTER JACCHIA SMITHSONIAN ASTROPHYS. OBS. SP. RPT. 100)

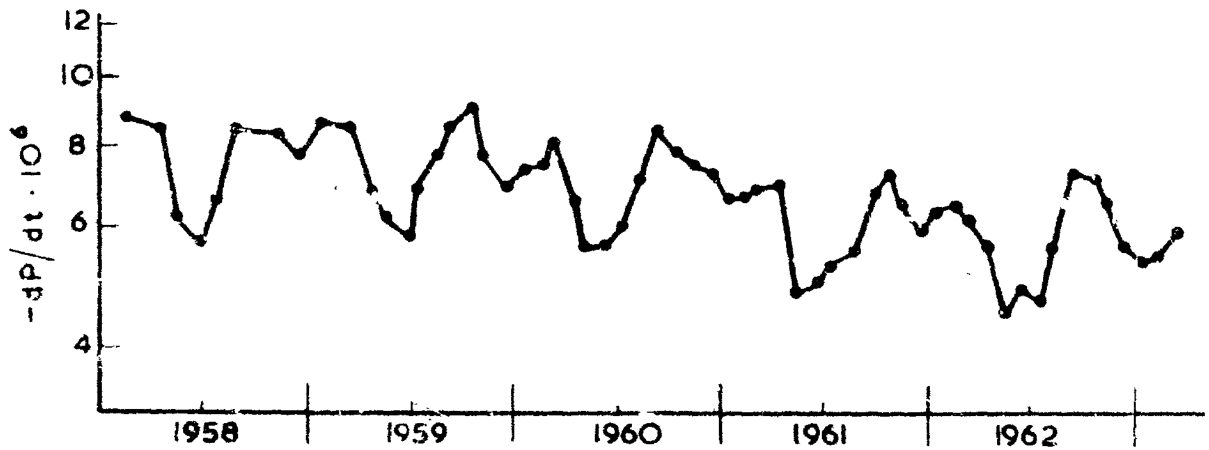

Fig. 10 RATE OF CHANCE OF ORBITAL PERIOD FOR EXPLORER I, CORRECTED TO ALLOW FOR VARIATIONS IN SOLAR ACTIVITY, GEOMAGNETIC INDEX AND DAY-TO-NIGHT EFFECT. AFTER PAETZOLD

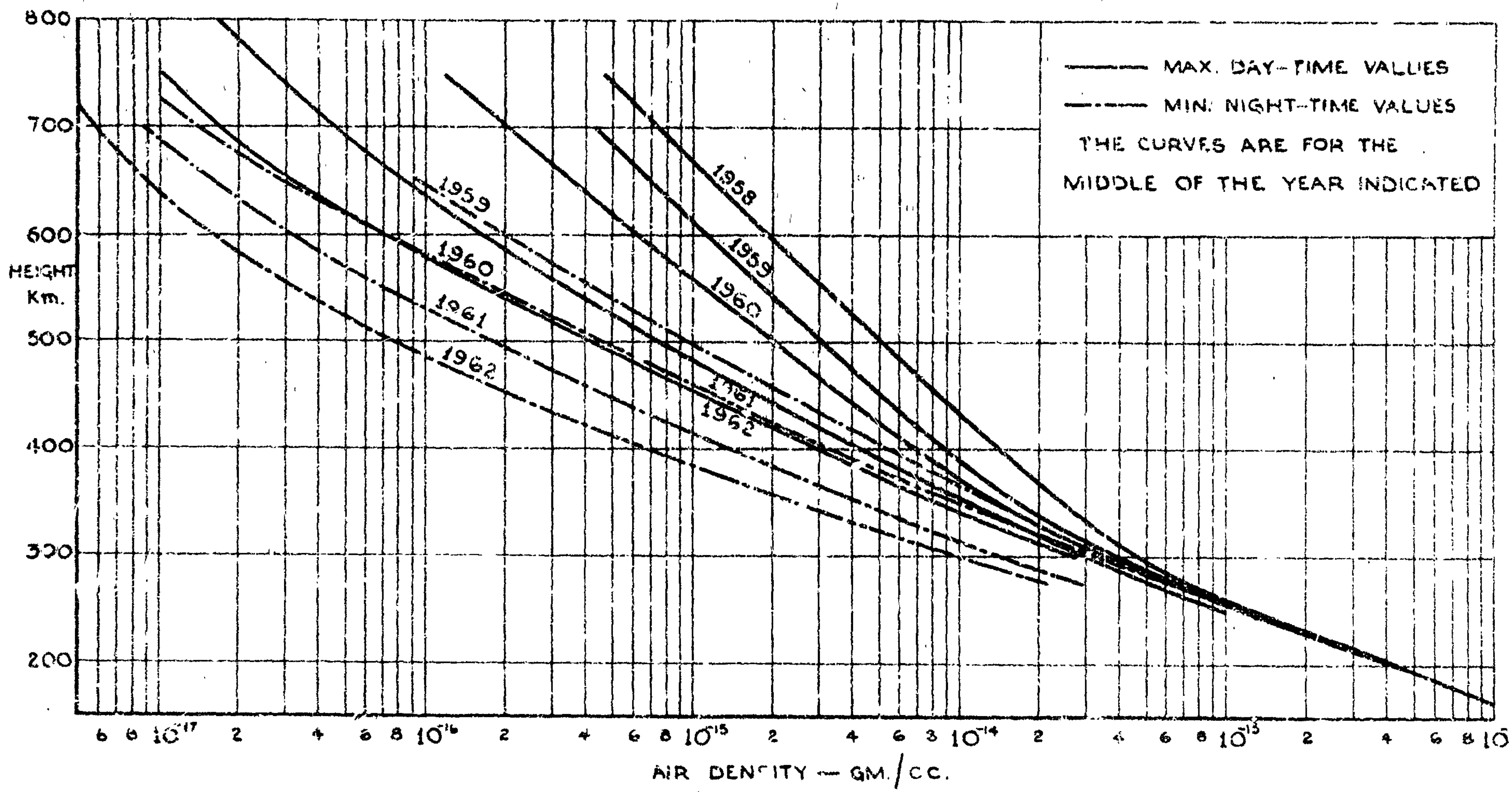

Fig. 11 VARIATION OF AIR DENSITY WITH HEIGHT FOR THE YEARS 1958-62

EARTH'S ATMOSPHERE - COMPOSITION - NEW MODELS

BY

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(Paper is not available for publication)

NEAR EARTH ENVIRONMENT

N65 15485

THE METEOR POPULATION

BY

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THE METEOR POPULATION

by

Gerald S. Hawkins[1]

Introduction

The earth is continually bombarded with objects from outer space, and by studying the material as it arrives at the earth we can gain an understanding of the nature of the objects in the earth's environment. These objects cover a tremendous range of mass, from millions of tons to 10^{-16} gm, and their physical characteristics depend upon their masses. When the mass can be measured in kilograms, the object is invariably a solid piece of stone or iron, or stone and iron mixed. It is able to penetrate the atmosphere of the earth completely and land upon the surface. After retrieval, the object is known as a meteorite.

Between masses of approximately 10^{-12} gm and 10^{2} gm the particles are meteors that have been derived from the icy nucleus of a comet. Meteor particles invariably disintegrate in the upper atmosphere and never reach the surface of the earth intact. The population in the lower mass limit (10^{-12} gm) is composed of small particles that are decelerated without destruction in the upper atmosphere. These are known as micrometeorites and it is possible to collect them with high altitude rockets, or retrieve them as they float down to the surface of the earth.

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The influx of objects into the earth's atmosphere is now fairly well established for the entire meteor population. The results of various measurements, given in Fig. 1, show that the number of particles falling into the earth's atmosphere increases with decreasing mass. It is also possible now to draw a monotonic curve over the entire range from micrometeorites to meteorites. The characteristics of the various groups in the meteor population are described

Meteorites

The statistics pertaining to the fall of meteorites is based at present on an inhomogeneous set of data. More than 1,000 eye-witness accounts, mostly non-professional, are available of the fall of a meteorite that later was recovered and whose mass was determined. Several analyses in which the vagaries of the collection technique have been partially allowed for (Nininger 1933, Öpik 1958, Hawkins 1959, 1960, 1963a, and Brown 1960) have been made to determine the rate of arrival of meteorites. A photographic network is now being constructed in the Prairie regions of the United States to obtain more reliable statistics (McCrosky 1963), but until fresh data are available we must rely upon the meteorite catalogues.

Meteorites are classified as stones or irons. The stones contain minerals such as olivine, pyroxene, plagioclase and troilite, and have an average density of 3.4 gm cm^{-3}. Most stones contain chondrules, small spherules about 1 mm in diameter; they are usually a mixture of orthopyroxene and olivine.

The irons are largely metallic, being coarse crystals of an iron-nickel alloy. The percentage of nickel varies from about 3 to 15, and the average density is 7.8 gm cm^{-3}.

The crushing strength for stone meteorites varies from 3.8×10^6 gm cm^{-2} to 6.3×10^4 gm cm^{-2}, although one or two meteorites have crumbled at values somewhat lower than this. The average crushing strength for stone is approximately 3×6 gm cm^{-2}. The crushing strength for an iron is considerably higher, although occasionally an iron will break up under moderate stress because of weaknesses in the boundary between adjoining crystals.

It has been shown (Hawkins 1963a) that the stone and the iron meteorites differ in their mass distributions. The number N of stones that fall on one square kilometer of the earth's surface during the period of a year, with mass greater than or equal to m, is given by the relation

$$\log_{10} N = -0.73 - \log_{10} m \qquad (1)$$

Note that N is a cumulative number that is of direct interest in the problem of space hazards since it gives the total number of impacts of objects above a certain limiting size. Equation (1) gives the influx as a function of the mass "in space" of the meteorite; this mass will be considerably reduced by ablation processes in the atmosphere. The number of irons that impact is given by the relation

$$\log_{10} N = -3.51 - 0.7 \log_{10} m \qquad (2)$$

It can be seen from these equations that the cumulative number of stony meteorites varies as m^{-1}, whereas the number of irons varies as $m^{-0.7}$. This represents a difference in the mass distribution of the objects, which is important for several reasons. Firstly, although the average-sized meteorites are usually stones, extremely large meteorites are usually irons. At a mass of 100 kgm the stones outnumber the irons in the ratio 20:1. At a mass of 10^{10} kgm the irons outnumber the stones by 10:1. Stones and irons occur in equal numbers at a mass of about 10^6 kgms, which forms a convenient point at which to divide the two regimers of meteorites. Secondly, the mass distribution yields information concerning the origin of the meteorites. Equation (1) is the same as the comminution law obtained when terrestrial rocks are subjected to grinding and crushing for a considerable length of time. Equation (2) represents a moderate degree of crushing. This is consistent with the hypothesis that meteorites are asteroidal fragments formed by collision processes in space and that the stone fragments have been crushed to a greater degree than the irons, owing to their low crushing strength (Hawkins 1960). Thirdly, Equation (2) is consistent with the number of asteroids that cross the orbit of the earth, and we may conclude that objects such as Eros, Apollo and Amor are probably composed of iron.

Cometary Meteors

Although a few stone and iron fragments with masses less than 100 gm are undoubtedly present in the meteor population, the bulk of the material in this range is the solid debris ejected from the icy nucleus of a comet. At least 50 per cent of cometary meteors are sporadic; the orbital elements form a smooth distribution and there are no discernible sub-sets. It is therefore necessary to describe sporadic meteor orbits on a statistical basis. The flux of sporadic meteors, N km^{-2} $year^{-1}$, is given as a function of the mass, m gm, by the relation:

$$\log_{10} N = +0.4? - 1.34 \log_{10} m \qquad (3)$$

The result has been obtained from a photographic survey (Hawkins and Upton 1958). In the original determination the mass of a meteor of a given brightness was not known with certainty and equation (3) is based upon a revised scale in which the mass of a meteor with zero visual magnitude and a velocity of 30 km sec^{-1} is 4.4 gm. There are still uncertainties in the mass scale (Whipple 1963, Lazarus and Hawkins 1963), but equation (3) is probably trustworthy to within a factor of 5. There are diurnal and seasonal variations in the meteor flux which are of the same order of magnitude as the uncertainty in equation (3).

Approximately 50 per cent of the meteor flux comes from the major and minor streams, and must be added to the sporadic flux. Several of the major streams, such as the Perseids and Taurids, are related to known comets. Other streams are not associated with a known comet, and presumably the parent comet has disintegrated. The most important of these streams are listed in Table 1. The flux from streams is limited to a few days of maximum activity on certain calendar dates, and during these periods an extra component, N_s, is added to the flux. If we define the stream activity in terms of the sporadic rate such that $N_s = kN$, then the factor K is that given in Table. 1.

TABLE 1

Stream Flux

Stream	Dates	k
Quadrantids	Jan 2-3	5.0
Lyrids	Apr 20-21	0.5
Daytime Arietids	June 5-11	5.0
Daytime ζ Perseids	June 5-11	4.0
λ Aquarids	July 22 - Aug 7	2.0
Perseids	Aug 9-14	5.0
Orionids	Oct 20-24	2.0
Taurids	Oct 10 - Nov 25	0.5
Geminids	Dec 10-16	5.5

Stream meteors, of course, move in almost parallel paths and the flux given in Table 1 is for an area continually oriented in a direction perpendicular to the stream.

Photographic observations have shown that cometary meteors are extremely fragile. Meteors with an initial mass of approximately 100 gm shed fragments continually during the luminous trajectory in the upper atmosphere (Jacchia 1955). At smaller sizes, at a mass of approximately 0.1 gm (visual magnitude +3), the meteor occasionally disintegrates at the beginning of the luminous trail (McCrosky 1955). From the height at which disintegration takes place and from the velocity of the meteor, it is possible to calculate the dynamic pressure exerted on the body. One meteor in three, in this range, breaks up when the pressure exceeds 10 gm cm^{-2}. This is an extremely low crushing strength by terrestrial standards, comparable to that of cigar ash.

Whipple (1963) has discussed the photographic observations made on meteors with masses between the approximate limits of 1 gm and 100 gm, and with an average density close to 0.4 gm cm^{-3}. From this low density and the low crushing strength it has been inferred that cometary meteors are loose aggregates of small particles forming an open or porous structure. The solid particles are presumed to be composed of minerals similar to those found in stony meteorites, although no direct chemical analyses have been made so far because the meteor material is too fragile to reach the surface of the earth in any large quantities. Spectrograms of brighter meteors show the presence of iron, calcium, sodium, silicon and other relatively abundant elements. It has not yet been possible to obtain spectrograms of meteors fainter than a magnitude ~ 0, corresponding to a mass of 5 gm.

Equations (2) and (3) and Figure 1 show that the flux of cometary meteors equals the flux of meteorites at a mass of approximately 300 gm. The regime of cometary meteors has been defined by extending equation (3) from a mass of 300 gm to a mass of 10^{-13} gm. At first sight this extrapolation might seem unwarranted since the photographic observations do not extend below a mass of 10^{-2} gm. However, since there is confirmation from radar data at a mass of 10^{-4} gm, and since the extrapolation agrees with the number of particles collected by high altitude rockets at a mass of 10^{-13} gm, this extrapolation is probably valid to perhaps an order of magnitude.

Using a six-station radar system (Hawkins 1963b), Hawkins and Southworth (1963) have studied the influx rate and physical characteristics of meteors close to the middle of the range of cometary meteors. Preliminary measurements of the flux of meteors with mass greater than 4×10^{-4} gm yields the value shown in Figure 1. The determined value is an order of magnitude greater than the value expected from Equations (3) and further work is required to investigate this discrepancy. However, considering the degree of the extrapolation, the point may be taken as a preliminary confirmation of Figure 1.

The small particles investigated by the radio technique clearly show the effects of fragmentation. At the limit of velocity measurements, 10^{-3} gm, most of the meteors are observed as a closely packed cloud of many independent fragments. The meteor has totally disintegrated at or before the onset of ionization. Because of this effect, the density of the meteor before breakup cannot be measured. However, it is presumed that the density in space is comparable to the value of 0.4 gm cm^{-3} as found for the larger objects observed in the photographic program.

Definite changes appear in the orbits of sporadic meteors as one proceeds from a mass of 1 gm to a mass of 10^{-3} gm. As one proceeds to smaller masses the orbits show smaller semi-major axes and smaller eccentricities. This effect is apparent from a detailed study of the orbital distributions as a function of mass. The effect can also be shown statistically by comparing the average observed velocities of sporadic meteors as a function of mass. Figure 2 shows the average velocity over a range of visual magnitudes from +6 to +9. There is a general decrease in velocity amounting to approximately 5 km sec^{-1} over an interval of 3 magnitudes (Hawkins, Lindblad and Southworth, 1963a). A similar result has been obtained for meteors with radiants near the Apex by Eshleman and Gallagher (1962), who found that between magnitudes of +7 and +12 the average sporadic velocity decreased by 2 km sec^{-1}. This value is probably an underestimate because Eshleman and Gallagher did not determine any values of velocity below 35 km sec^{-1}.

These authors have suggested that at a mass of approximately 10^{-4} gm "The so-called sporadic background appears instead to consist of particles concentrated into a very large number of shower orbits. Characteristic dimensions of these particle concentrations must be very small, by astronomical standards, since the intersection of a group with the earth may take on the order of one day or less. It is suggested that the earth may be immersed in about ten particle groups at one time. It appears that there may be millions of such groups in the solar system ..." These conclusions were based upon an interpretation of the fluctuations in hourly rate reported by a sensitive radar system. They are not borne out by a detailed study of the orbits of meteors in this size range. A comparison program has been carried out on 2300 meteor orbits with masses between 10^{-1} and 10^{-3} gm. (Hawkins, Lindblad, and Southworth 1963b). Most of the streams found were the well known major and minor streams previously discovered visually and photographically. There is no detailed structure within the sporadic orbits, and it is therefore possible to describe them only in terms of broad statistics.

Approximately 30 per cent of sporadic meteors at a mass of 10^{-2} gm are moving in orbits of low eccentricity and high inclination (Davies and Gill 1960; Hawkins 1962). This is quite different from the alignment in the plane of the solar system found in photographic measurements. This second grouping has been provisionally called the "toroidal group," which was probably formed by the long-term perturbations from the planet Jupiter.

Micrometeorites

The deceleration of a meteor in the atmosphere depends on the ratio of cross-sectional area to mass. Thus, the deceleration is inversely proportional to diameter, and small objects undergo a severe deceleration. Whipple (1950) and Öpik (1937) have pointed out that a small object can de decelerated without melting, and arrive at the surface of the earth intact. These objects are aptly termed micrometeorites, and their recovery at ground level and in the upper atmosphere is of great interest.

Whipple (1950) assumed that the energy generated by passage through the upper atmosphere is quickly conducted to the interior of the micrometeorite. The object then reradiates this energy as a gray-body in isothermal surroundings, and will remain solid provided that the surface temperature does not rise above the melting point of the material. The critical size of a solid micrometeorite is given in Table 2 as a function of velocity and density of the object. If the meteor melts, it will still escape destruction if the temperature remains below that of vaporization. Under these conditions the maximum diameter will be somewhat greater than those given in Table 2. A micrometeorite of the size given in Table 2 reaches a maximum temperature at a height which is approximately 10 km above the beginning height of cometary meteors. The particle decelerates rapidly after attaining maximum temperature and soon reaches a terminal velocity. Micrometeorites smaller than those listed in Table 2 are decelerated more rapidly, and reach a maximum temperature at higher heights than those given in Table 2.

Several methods have been used to collect micrometeorites. Sticky plates have been exposed at ground level in dust-free regions. Microphones have been carried on high altitude rockets and satellites to detect the impact of small objects. The most direct method, and the one that is perhaps less subject to contamination and misinterpretation, is the rocket-borne collection and recovery technique of Hemenway and Soberman (1962). A collector rocket was fired from White Sands, New Mexico, on 6 June 1961, reaching an altitude of 168 km. Several space layers of Mylar foil were exposed to determine the rate at which the foil was punctured. Several types of collecting surfaces were also exposed to trap the micrometeorites upon impact. Extreme care was taken to avoid the possibility of terrestrial contamination. Before launching, all collecting surfaces were coated with a thin film of nitrocellulose film. The collecting surfaces were shadowed by an atomic beam both before launching and after recovery, so that extraterrestrial particles could be readily identified.

TABLE 2

Micrometeorite diameters

Velocity ($km\ sec^{-1}$)	Height of maximum temperature (km)	Maximum diameter, Density = 3	(Microns) Density = 0.3 $gm\ cm^{-3}$
15	92	38	380
20	96	18	180
25	100	10	100
30	103	6	60
40	108	3	30
50	113	1.4	14
60	117	0.9	9
70	120	0.6	6

Millions of particles were collected during approximately 200 seconds of exposure but, of course, only a sample of these particles could be investigated. In general the particles could be divided into three types as illustrated in Figures 2, 3, and 4. Figure 2 shows what was termed a "fluffy" particle, very irregular in shape and open in structure. During its interaction with the atmosphere, a particle of this type would necessary exhibit a low effective density. A loose aggregate of this type is remarkably close to the physical characteristics derived for cometary meteors from photographic studies. Figure 3 shows a more compact object that, like the particles in Fig 2, has not melted during deceleration. Figure 4 shows a small spherule and the crater that it formed in the aluminum coating on nitrocellulose film.

Note that the typical particles shown in Figures 2, 3, and 4 are well within the size range of micrometeorites as given in Table 2. The particles must have arrived at the collecting films at very low veloctiy. For example, the sphere in Figure 4 did not carry sufficient energy to puncture the thin nitrocellulose film that backed the aluminum layer. This indicates that the particles were falling with terminal velocity in the atmosphere and is further confirmation that the particles are micrometeorites.

Hemenway and Soberman give the observed flux of particles on the collecting surfaces of the rocket as a function of the size of particle. To obtain the true influx of micrometeorites it is necessary to apply a correction for the velocity of the rocket. It is assumed that all particles were falling through the atmosphere with terminal velocity and that the flow of particles in each size range had reached a condition of steady state. Under these conditions the observed flux would be the true flux if the rocket were stationary. A correction factor was then applied to allow for the vertical motion of the rocket. Assuming a mean density of 3.0 gm cm^{-3} we may represent the flux by the expression

$$\log_{10} N = 12.43 - 0.39 \log_{10} M. \qquad (4)$$

The cumulative flux, N, is the number of particles km^{-2} year^{-1} with mass greater than or equal to m gm.

Equation (4) was found to hold for particles with diameters up to 2.5 microns, corresponding to a mass of approximately 10^{-13} gm. At this diameter a pronounced change appeared in the gradient in the mass distribution, and the value agreed with that of equation (3) within the limits of experimental error. Thus it is reasonable to presume that the regime of cometary meteors extends to masses as small as 10^{-13} gm. As further corroboration, note that the absolute value of flux at 10^{-13} gm is in agreement with the absolute value determined by extrapolating the photographic data. It is also in fair agreement with the flux determined by microphone impacts. (Dubin and McCracken 1962) Hemenway and Soberman (1962) attribute the change of slope in the mass distribution to the effects of radiation pressure acting on the particles in interplanetary space.

The extraterrestrial particles were examined with an electron microscope, which yielded the photographs in Figures 2, 3, and 4. Individual particles were examined by an electron diffraction technique to test for crystal structure. An electron probe was used to excite X-ray fluorescence to determine the chemical constituents. One or two particles were subject to neutron activation to search for specific elements.

The majority of the particles showed no detectable crystal patterns. The reason for this has not been established, although various possibilities suggest themselves. The small particles formed in interplanetary space may be completely amorphous; the particles may be composed of a multitude of minerals in micro-crystalline form; the particles, although originally crystalline, may be heated sufficiently to destroy the crystal structure during passage through the atmosphere. Of these suggestions, perhaps the second is the most likely. The fluffly fragments show evidence of being composed of microscopic particles with individual masses of about 10^{-15} gm. If these particles represented a hundred or more different minerals, then no crystal pattern would be detected. Approximately one micrometeorite in a hundred does show a definite diffraction pattern. These exceptional particles contain a predominant mineral. Although several crystal spacings have been determined, the nature of the mineral has not been identified.

Most of the micrometeorites examined do show a crystal pattern when the particle has been vaporized in the electron beam and recondensed on the adjoining film. The most predominant diffraction pattern observed corresponds to three possible cyrstal structures - austenite, taenite, and copper. It has not been possible to decide which of these possibilities is correct, although it should be noted that taenite is a well-known constituent of the larger meteorites.

The electron probe and neutron activation show the presence of the following chemicals: Al, Si, Fe, Ni, Ti, Ca, Mg, and Cu. The abundances varied from particle to particle although aluminum, silicon, and iron were frequent constituents. There was a possibility that the aluminum and copper had been introduced as contaminants.

Space Hazards

The flux shown in Figure 1 represents a revision of the estimates given by Whipple (1963), and covers a greater variation of mass. The physical characteristics of the projectile are given as a function of mass, and the population may be conveniently divided into the four regimes - irons, stones, cometary meteors, and micrometeorites. The results, and our current knowledge of penetration and cratering, can be used to estimate the damage sustained by a space craft. For example, Herrmann and Jones (1962) have shown that the depth p of a crater, formed in a semi-infinite target by a projectile of mass m, is given by the semi-empirical relation

$$p = 1.70\, m^{1/3}\, \rho^{1/3}\, \rho_t^{-2/3}\, \log_{10} (1 + 0.25\, \rho^{2/3}\, \rho_t^{1/3}\, v^2 H^{-1}) \qquad (5)$$

where ρ is the density of the projectile, ρ_t is the density of the target, v is the impact velocity and H is the Brunell hardness. Equation (5) is given in cgs units. A thin plate of thickness P will be punctured if (Whipple 1963)

$$P \leq 1.5\, p. \qquad (6)$$

At the large end of the mass scale of the meteor population the problem is to calculate the probability that a surface will be punctured during flight. At the small end of the mass scale the problem is to compute the rate of erosion of the surface caused by many successive impacts.

As an example, the probability of collision for Project Apollo is also given in Figure 1. The probabilities are based on an estimated cross-section of 10 m^2, and an exposure time of 10 days. The probability of collision with a stone or iron meteorite is trivially small, although, of course, the effects of impact would not be so trivial if they did occur. No space craft could be designed to withstand the catastrophic effects of collision with a meteorite. At a mass of

10^{-5} gm the probability of collision is 1.0. According to the impact theory this is sufficient to penetrate an aluminum skin of thickness 0.05 cm if the meteor density is 0.4 and the velocity is 22 km per sec^{-1}. At a mass of 10^{-12} gm, the Apollo vehicle will suffer 10^{10} collisions. This will produce approximately 1000 erosion pits per mm^{-2}.

In using equations (3) and (4) to estimate space damage several factors have to be borne in mind. It has been suggested that the space density of micrometeorites decreases as one proceeds away from the vicinity of the earth (Whipple 1961), although there is still some uncertainty in the result (Dubin and McCracken 1962). If a dust cloud does exist in the vicinity of the earth, then the flux given in Equation (4) may be considerably reduced in deep space. The micrometeorites detected by rocket were assumed to be falling with terminal velocity. Thus, a satellite moving through the layer of micrometeorites will tend to sweep up particles at a rate greater than that given in Equation (4). The flux will be increased approximately by the ratio of the velocity of the space craft to the terminal velocity of the micrometeorites. For both micrometeorites and cometary meteors a certain amount of shielding is produced by the earth itself. The value of N in Equations (3) and (4) is reduced, although never by more than a factor of 2 for a randomly oriented space craft.

IONOSPHERE

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The Neutral Atmosphere

The decisions as to the mechanisms governing the characteristics of ionospheric ions and electrons depend heavily on our knowledge of the ionizing radiations, the absorption and ionization cross-sections of the ionizable constituents, and of the structure of the neutral atmosphere. The important atmospheric structural parameters are temperature, composition and density. Rocket grenade and pitot-static-tube experiments conducted on an international scale have contributed significantly to reference atmospheres below 100 km and have recently reviewed by LaGow and Minzer [(40)].

Unfortunately, because of relatively few direct measurements, models of neutral gas parameters above 100 km depend heavily on theoretical application of the hydrostatic law to assumed boundary conditions at uncertain altitudes of diffusive separation. There is general theoretical agreement that maximum heating occurs between 100 and 200 km while above this level conduction keeps the temperature at a nearly constant level for any geographic location. A typical vertical temperature distribution [(34)] is illustrated in Fig. 1a. A theoretical model of the fractional composition of the atmosphere below 500 km is illustrated in Fig. 1b. This model is proposed by Johnson[34] who emphasizes the uncertainties involved. From the standpoint of the physics of the lower ionosphere one critically needs to know the ratios O/O_2 and O/N_2. According to Schaefer[52], the early rocket rf mass spectrometer O/O_2 results of US[42] and USSR[47] investigators are subject to question because of the high probability of surface recombination effects within the instruments. Schaefer obtained a ratio for O/O_2 of 0.5 at 110 km by use of a rocketborne massenfilter. According to LaGow and Minzer[40], this result agrees with that derived from ultraviolet absorption measurements by Hinteregger[25] and Kupperian et al[39] and that these results together can be expected to change some model atmospheres markedly.

Harris and Priester[24] have proposed a time-dependent model atmosphere assuming time invariant boundary conditions at an assumed altitude for diffusive separation, assumptions which have not yet been verified experimentally. In Fig. 2a are illustrated their curves of the altitude dependence of mean molecular weight at the diurnal extremes for both solar maximum and solar minimum conditions. These curves infer the variability of the thickness of the helium region in the exosphere, the existence of which was first suggested by Nicolet[44]. It generally is agreed from satellite drag determinations[29,36,46] that temperatures in the isothermal altitude region (above 200 km) exhibit a large diurnal and solar cycle variation and that these can be related empirically to the flux of decimeter radiation observed at the earth. The temporal thermospheric temperature variations inferred by Harris and Priester are illustrated in Fig. 2b where the indices of decimeter radiation S = 250 and S = 70 correspond respectively to solar maximum and minimum conditions. Superimposed on these are "27-day" and semi-annual fluctuations, the latter leading to the suggestion(30) of a secondary heat source associated with the solar wind. Although the general shape of the temporal variation of thermospheric temperature appears to be agreed upon by workers in reference atmospheres, it should be pointed out that a direct measurement by French investigators of the neutral gas temperature with the use of a rocketborne sodium release experiment(11) exhibits a value higher in absolute magnitude than most reference atmospheres including that shown in Fig. 2b.

Satellite drag determinations have yielded considerable information on atmospheric density above 200 km. The Harris and Priester density model which is illustrated in Fig. 2c for an altitude of 600 km is consistent with these previously determined results. Direct checks of densities deduced from satellite drag measurements have been made by pressure gages flown on the Sputnik 3 and US(53) satellites. Density is perhaps the best known neutral gas parameter for altitudes above 200 km.

D Region Electron Densities Under Quiet Solar Conditions

Spaceflight observations made during the absence of solar flares show that the three most probable ionizing agents for the mid-latitude D region (50 - 85 km) are cosmic rays, Lyman α (1215.7Å) and X-radiation (2-8Å). The Lyman α energy flux (3-6 erg cm^{-2} sec^{-1}) is relatively constant with solar condition. Measurements made principally from US(19) and British(49) satellites show that the X-ray energy flux, on the other hand, is extremely variable (Fig. 3).

Theoretical models are harmonious in characterizing the region below 70 km as one produced by cosmic rays and containing a high negative ion density (n_-). However, there is some discord in the hypotheses for the formation of the 70-85 km region, some models(43,45) preferring the action of Lyman α radiation on nitric oxide, a trace constituent, to the ionization of the major atmospheric constituents by X-radiation (48).

Electron density (n_e) profiles for the "quiet" D region have been measured from rockets with rf probes by USSR investigators (37) and with a Faraday rotation technique involving transmission from the ground to the rocket of a 3 Mc/s signal by a team of US-Norwegian investigators (1). The latter result (Fig. 4) is quite consistent in the 70-85 km with that obtained (9) in Canada by ground-based methods. In their discussion of the result illustrated in Fig. 4, the investigators emphasize: (a) that the electron abundance in the region believed to be produced by cosmic rays is higher than theoretical expectation; (b) that even using fluxes typical of a disturbed sun, X-radiation is insufficiently energetic to account for the observed ionization at altitudes between 70 and 85 km (theoretical curve II); (c) that the experimental electron density profile is better fitted by the Lyman α hypothesis (theoretical curve I); and (d) that the minimum in electron density at 83.5 km which coincides with the mesopause is possibly due to either a decrease in the NO concentration or to attachment of electrons to dust whose existence has been detected at this altitude by rockets flown in Sweden (56).

D Region Ion Densities

There have been preliminary experimental attempts to describe the ionic characteristics of the D region by Japanese (3,4,27) and US (12,50,54,60) workers, using different techniques but all involving direct sampling of the rocket's environment. The need for additional theoretical work to permit translation of the measured ion currents into meaningful geophysical parameters at altitudes below 90 km has been emphasized by some of these investigators (27,60). This precautionary statement applies throughout the discussion of Fig. 5 which summarizes those positive ion density (n_+) profiles reported for the entire D region. As with the n_e values in Fig. 4, all three profiles show a higher n_+ abundance than theoretical models for the cosmic ray-produced region below 70 km. The order of magnitude difference in the profiles at altitudes 70-85 km would not be expected from data presumably obtained under similar solar conditions.

Ion densities measured by Japanese workers are not included in Fig. 5, only because they do not extend below 80 km. At 80 km, their spread of values brackets Whipple's result. Between 75 and 85 km, the n_+ values reported by Whipple agree within a factor of 2 with the n_e values from Fig. 4. This in turn is in qualitative agreement with the theoretical D region models of Nicolet and Aikin[45] and of Whitten and Poppoff[62] which claim a negligible n_- above 70 km. On the other hand, the model of Moler[43] contains a ratio of 10 for n_-/n_e at 70 km which would be more consistent with the Smith and Sagalyn experimental n_+ profiles. It is obvious that more work is required to (a) bring the theoretical D region models into closer agreement and (b) determine if the wide spread in the reported n_+ values is real or represents the need for refinement of the experimental techniques.

The Disturbed D Region

There are many phenomena which enhance D region ionization and a resulting increase electromagnetic wave attenuation. The measured degree of n_e enhancement for different types of events is illustrated in Fig. 6. The measured quiet sun profile from Fig. 4 is included for comparison.

Simultaneously with the appearance of a solar flare, radio absorption is observed in the D region on the sunlit side of the earth for periods lasting up to approximately one hour (Sudden Ionospheric Disturbance). It is possible to ascribe the increased ionization to abnormally high X-ray fluxes which were observed from rockets[(16)] at extremely low D region altitudes. An empirical correlation has been found[(19)] between the occurrences of radio fade-outs and the times when the X-ray flux (<8 Å) measured on the GREB satellite exceeded a critical value of 2×10^{-3} erg cm^{-2} sec^{-1}. S. I. D. electron density profiles have not been measured from rockets. However, a profile (curve C) illustrated in Fig. 6 was obtained experimentally at the time of a 2^+ flare by Belrose and Cetiner[(9)] using ground-based methods.

The influx of energetic protons at auroral latitudes during solar flares produces enhanced ionization (Polar Cap Absorption) unique to this latitude region. Rocket measurements of the n_e profile during a PCA event are limited to the result (curve E of Fig. 6) of Jackson and Kane[(31)] obtained during the early phases (3 db absorption at 30 Mc/s) of the event by use of the familiar Seddon CW propagation experiment.

At high latitudes, the D region frequently is characterized by auroral type absorption. Aikin and Maier[(2)] have treated this phenomenon theoretically, attributing the enhanced ionization to direct (above 70 km) and indirect (bremsstrahlung below 70 km) effects of penetrating energetic electrons. Their theoretical profiles are in approximate agreement with the rocket result (curves B and D in Fig. 6) obtained under varying degrees of auroral absorption by a team of Danish and Norwegian investigators[(32)] who used ground-to-rocket propagation experiments.

D Region Electron Collision Frequencies

Together with the existence of free electrons, the inherently high electron collision frequencies make the D region the most important ionospheric sub-division from the standpoint of radio absorption. The early rocket electron collision frequency measurements of Kane[35] now have been supplemented by the Danish-Norwegian workers[32] from the FERDINAND rocket program. In their summary (Fig. 7) of the overall results, the latter suggest that their data and that of Kane possibly can be separated into two groups to illustrate a seasonal effect.

Solar Radiation Intensity in the E and Lower F Regions

Significant contributions to the physics of the E and lower F regions have resulted from rocket measurements of solar EUV intensity. These data tend to explain qualitatively the general characteristics of electron density profiles measured in the lower ionosphere. Two such n_e profiles, one obtained by the Japanese with their resonance probe[3] and the other by a CW propagation experiment[8] are shown on the right-hand side of Fig. 8. These profiles confirm earlier rocket measurements in showing (a) the high n_e gradient which constitutes the base (85-100 km) of the E region and (b) that the lower daytime ionosphere is characterized by a monotonically increasing electron density rather than distinct layer separation between the E and F regions.

Hinteregger and Watanabe[26] have conveniently classified the former's solar radiation data into four groups. The altitude dependence of the flux of the strongest feature in each group is illustrated in the left-hand side of Fig. 8 as follows: C III in the band 1027-911Å, the Lyman continuum in the band 911-796Å, He I in the band 630-465Å and He II in the band 370-280Å. The discussion which follows is principally their interpretation of the relative importance of EUV radiation to ionization profiles such as those shown in Fig. 8.

Only the region below 120 km is dominated by a single group (1027-911Å). This is evident from the depth of penetration of C III shown in Fig. 8. Hinteregger and Watanabe conclude that absorption of C III and H Ly-B (1025.7Å) is more effective than that of soft X-rays (10-170Å) to the ionization of the 100-120 km region. Other investigators insist that soft X-rays comprise the dominant source of ionization at these altitudes. Of the two EUV lines, the base of the E region (below 100 km) is dominated by H Ly-B although other investigators additionally include 30-100Å X-rays.

Above 120 km, the three remaining EUV groups (911-280A) each contribute to the electron production. The superpositioning of the contributions from each group is such that no "layers" of the simple Chapman type would be expected in the lower ionosphere, a conclusion verified by the relative smoothness of the measured electron density profiles shown in Fig. 8.

Ion Production and Abundance in the Lower Ionosphere

Watanabe and Hinteregger[59] have combined rocket data on UV fluxes with an assumed model atmosphere to infer the altitude dependence of photoionization rates as a function of wavelength (Fig. 9a) and of the rates for production of individual species O_2^+, O^+ and N_2^+ (Fig. 9b). They emphasize, in view of the uncertainty in our knowledge of atmospheric composition as discussed briefly in section 1.1, that these curves are suggestive rather than quantitative.

Some indication of a few of the important lower ionospheric reactions has evolved by a comparison of such inferred production rates with the results from rocketborne ion spectrometers obtained by US[33,57] and USSR[28] workers. These results agree in identifying the three most abundant ions below 200 km as O_2^+, NO^+ and O^+ with the latter becoming the most abundant above this level. Typical of these data is the mid-latitude result (57) shown in Fig. 9c. The most likely explanation for the identification of N_2^+ as a trace ionic constituent even though its rate of production is high is its correspondingly high dissociative recombination rate ($N_2^+ + e \rightarrow N' + N''$). The existence of NO^+ as an important E-region ionic constituent even though it is not directly produced is probably explained by ion-atom interchange, specifically $O^+ + N_2 \rightarrow NO^+ + N$.

The Diurnal Behavior of the E Region

The recent introduction into rocket experimentation of ion and Langmuir probes with their high sensitivities permits our first insight into the diurnal characteristic of the E region. Some of the Japanese (41) n_+ and the US n_e (54) results are collected in Fig. 10 to illustrate this diurnal behavior. Both groups concur in classifying the daytime E region as relatively smooth with no significant valleys of ionization. More importantly, their work together identify the nighttime profiles as having considerable irregularities superimposed on a deep n_e valley which tends to separate the E and F regions. These valleys are readily apparent at altitudes above 120 km in Fig. 10. Confidence in these data comes from the agreement which the Japanese obtained between their ion probe and n_e determined by their resonance probe in the daytime ionosphere and from a simultaneous comparison (55) for a daytime condition of the results from the Langmuir probe and a propagation experiment.

Another contribution from both sets of experiments has been additional description of the ionization characteristics of the sporadic-E or E_s, layer, an example of which[56] is shown in Fig. 11. Layers as thin as 0.45 km with a horizontal dimension of at least 72 km have been detected. Ionization enhancements of up to a factor of 10 above the average E region densities have been measured. Some of the prevailing theories[5,61] to explain E_s ionization suggest that in the presence of a magnetic field, transport toward the South on the low side of a wind shear and toward the North on the high side of the shear would result in concentration of the plasma at the altitude of zero velocity. However, these hypotheses have not been verified by the results from nearly-simultaneous launchings of two rockets, one to measure wind shear and the other n_e. The results[55] illustrated in Fig. 12 instead show that the E_s layer detected at 100 km is associated with an East-West shear in which the motion is toward the East below the layer and toward the West in and above the layer. As the results show, the relationship between E-region ionization and wind shear is not obvious.

Rocket Measurements of Electron and Ion Densities Above the F2 Peak

Most theoretical models explain the formation of the F2 peak as the result of competition between production, a height dependent loss rate and diffusion, with diffusion predominating above the F2 peak. Early rocket measurements of n_e above the F2 peak were made by Gringauz[20] and Berning[10].

Significant interpretations have come from upper ionosphere profiles obtained more recently. Scale height changes in such profiles have been interpreted mostly in terms of changes in ionic composition. Hanson[22] has suggested from a daytime ion density profile obtained by Hale that during 1960 the predominant ionic constituent at altitudes between 1200 and 3400 km was He^+, confirming Nicolet's suggestion that helium is an important constituent of the exosphere. From this same profile, it also was suggested that $(T_e+T_i)/2$ was constant with altitude with a value of 1600°K, where T_e and T_i are the electron and ion temperatures. It has since been shown that the two transition levels separating the O^+-He^+ and the He^+ -H^+ regimes exhibit a large diurnal and solar cycle variation. This is illustrated in Fig. 13 which contains a comparison of experimentally-obtained day and night profiles. Curve B obtained by Bauer and Jackson(7) has been interpreted by them as corresponding to a value for $(T_e+T_i)/2$ of 1300°K approximately constant with altitude with O^+ predominant below the apparent transition level and He^+ above. According to Donley(18), the experimental profile is consistent with a theoretical model by Bauer (curve A) and thus a much lower altitude of transition from heavy to light ionic constituents, the region just above the F2 peak corresponding to O^+ with $(T_e+T_i)/2 \cong 800$°K while the extreme upper portion corresponds to H^+ with $(T_e+T_i)/2$ also approximately equal to 800°K. Most of the rocket profiles extending to high altitudes have been interpreted in terms of an isothermal ionosphere in diffusive equilibrium. These results were obtained at restricted latitudes and during the middle of the solar cycle. Other data discussed in succeeding sections show that the concept of an upper ionosphere in diffusive equilibrium with T_e+T_i constant with altitude does not exactly apply in all latitude and temporal conditions.

Rocket Measurements of Electron Temperature

The interrelationship of electron (T_e), ion (T_i) and neutral gas (T_g)

temperatures is a sensitive and important index of reactions taking place in the ionosphere. Existing theoretical arguments (17,23) for the midday ionosphere suggest large departures from temperature equilibrium in the 150-300 km region but smaller temperature differences in the E and upper F regions.

Some altitude profiles of T_e now are available from rocket flights of the Japanese resonance probe (3) and from the work of Brace and Spencer (15) who used an ejectable symmetric Langmuir probe. The early resonance probe results were the first to show that temperature equilibrium could exist in the E region (3). These particular results were obtained almost simultaneously in time with one of the symmetric Langmuir probe flights. The results of Brace and Spencer are summarized in Fig. 14. The quiet day Wallops Island results are in good agreement with the Japanese E region data and the entire profile is consistent with the theoretical models of Hanson (23) and Dalgarno et al (17).

The remaining three profiles represent conditions where significant departures from temperature equilibrium can be expected at all altitudes, specifically under disturbed conditions at mid-latitudes and at high latitudes for both quiet and disturbed conditions. High E region electron temperatures also have been observed with the Japanese resonance probe (3). Although the data do not extend well above the F2 peak, three of the T_e profiles in Fig. 14 do suggest that the charged particle temperature is not always isothermal in this region, factor which would complicate the interpretation of electron density profiles in terms of T_e, T_i or ion masses. As discussed in a succeeding section, this conclusion is supported by Alouette satellite and ground-based backscatter results.

IONOSPHERIC RESEARCH RESULTS FROM SATELLITE EXPERIMENTS

Satellite Measurements of Electron Temperature

Extensive electron temperature measurements have been made on two satellites. A diurnal variation of T_e (Fig. 15) applicable to magnetically-quiet days (A_p<15) during November 1960 has been obtained from the Explorer VIII satellite on the questionable assumption that T_e is independent of altitude. Bourdeau and Donley[(14)] summarize the results as follows: (a) the average T_e obtained between 400-600 km during the six-hour period centered at midnight was 900°K with a standard deviation of 150°K; (b) the average T_e obtained at altitudes between 1000 and 2600 km during the six-hour period centered at 1300 LMT was 1600°K with a standard deviation of 200°K; (c) the most pronounced features of the data are the high values observed in the sunrise period at 600-900 km. In Fig. 15, these data are compared with the Harris-Priester T_g model corresponsing to the same epoch of the solar cycle.

With the benefit of a tape recorder, even more extensive measurements were made in the region 400-1200 km during April-June, 1962, by British investigators[(63)] with the use of the Ariel satellite. Their preliminary results which also assume an altitude-independent T_e are compared with the Harris-Priester T_g model in Fig. 16. Because of the large quantity of data, Willmore et al[(63)] have been able to show that T_e increases with latitude and thus suggest that corpuscular radiation becomes important at high latitudes.

Satellite Measurements of Ion Composition

Ionic composition has been measured with high resolution spectrometers on the Sputnik 3 satellite[(28)] and with spherical retarding potential analyzers on the Sputnik 3[38], Ariel[63], and Cosmos 2 satellite[21], and with planar retarding potential analyzers on the Explorer VIII satellite[13,14]. These results are generally consistent with each other and with Bauer's suggestion [6] that the upper ionospheric composition is strongly dependent on atmospheric temperature. This behavior is illustrated in Table 1.

TABLE 1. SUMMARY OF SATELLITE ION COMPOSITION RESULTS

Date	Time	Spacecraft	Altitude: $n(He^+)=n(O^+)$	Altitude: $n(H^+)=n(He^+)$
1958	day	Sputnik 3	>1000km	>1000km
1960	day	Explorer VIII	1200-1500km	>1800km
1962	day	Ariel	950km	>1200km
1960	nighttime	Explorer VIII	800km	>1000km
1962	nighttime	Ariel	<650km	1200km
1962	nighttime	Cosmos 2	570km	-

It is seen from the daytime results that the level where O^+ ions gives way to He^+ ions descended from above 1200 km to below 1000 km going from solar maximum to solar minimum. Under nighttime conditions, the O^+-He^+ transition altitude descended from 800 to about 570 km between 1960 and 1962. It should be noted that the detection of He^+ and H^+ ions now has been accomplished with a rocket-borne high resolution spectrometer[58].

Local Charged Particle Density Measurements from Satellites

Ion densities have been measured on satellites with spherical (38) and planar (13,21) ion traps. Additionally, Sayers et al (51) obtained large quantities of n_e values by use of an rf impedance probe on the Ariel satellite. Their most significant result is the detection of enhanced ionization which follow particular magnetic shells defined by a constant "L" value using the McIlwain notation. They report enhancement for L = 1.27 + .05, 1.09 ± .05 and approximately 1.75. Similar stratification was subsequently found in the Alouette satellite results discussed in the succeeding section. These "ledges" of ionization also indicate that in the topside ionosphere the electron density does not always decrease exponentially with altitude in a manner consistent with a vertical diffusive equilibrium distribution.

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GEOMAGNETISM AND THE IONOSPHERE

BY

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Abstract

The geometry of the magnetosphere and the dynamics of energetic particles and plasma trapped within it are discussed in relation to some problems of geomagnetism. Local acceleration of trapped particles is discussed, and the possible origins of electric fields and their roles in this and other magnetospheric phenomena are noted. It is found that many phenomena of interest may be newly interpreted in terms of the original Chapman-Ferraro theory of geomagnetic storms.

Author

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I. Introduction

Near the earth, many natural processes appear to be dominated by the geomagnetic field. In recent years, discoveries and observations made by artificial satellites and space probes have greatly extended our knowledge of these processes. The proliferation of such observations has in fact greatly strained our ability to interpret phenomena in the light of theory. This situation is by no means a new one in geomagnetism. For more than half a century, ionospheric research of importance to radio has been closely linked to that of importance to geomagnetism. As early as 1883, Balfour Stewart(1) suggested that ionized regions of the upper atmosphere might be the site of upper air winds blowing to produce varying electric currents, causing changes with time in the geomagnetic field. The possibility that more than one ionized region might be involved arose in the course of the further development of Stewart's dynamo theory of the geomagnetic variations.(2) The cause of the ionized regions was thought to be wave radiation. In addition, contributions of solar charged particles to the ionization at levels near 100 km was discussed by Birkeland(3) in his studies of the auroral-zone electric currents causing geomagnetic bays. He found that these electric currents must, on occasion, exceed 1,000,000 amperes, and hence require a considerable flow of ionized particles within the atmosphere. He also undertook experiments in which he propelled electrons within an evacuated chamber toward a small magnetized _terrella_ simulating the earth magnet. These experiments provided photographs of illuminated features on the _terrella_ and of ring currents at higher levels, which furnished graphic aids of inspirational importance to theoretical workers in geomagnetism and aeronomy over the 60 year period that followed. The concepts introduced by Birkeland, though based upon experiments in plasma physics, were discussed in terms of particle physics. The fluid concept of plasma physics had not yet been brought forward, though flow of electrical and magnetic energy as effluvia down geomagnetic field lines had been postulated in rudimentary form as early as 1693, in discussions of auroras, by Halley and others. It is therefore clear that some early studies in geomagnetism provided fundamental contributions to ionospheric research. Since some geomagnetic time variations arise from varying currents flowing in the ionosphere, and are dynamic manifestations of the ionosphere in motion, measurements of the geomagnetic variations supplement the information obtained from ionospheric soundings. Of course, most of our knowledge of the ionosphere has come from the exploration of the ionosphere by means of radio waves, propagated both upwards from the ground and downward from earth satellites moving above. Ionization has also been measured directly by rocket-borne instruments. The discovery of the Van Allen radiation belts and their subsequent exploration by artificial satellites and space probes added a new dimension to the problems of interest to geomagnetism. The interactions between the ionosphere and trapped energetic particles came to be recognized, and the electromagnetic effects of energetic plasmas imbedded in the geomagnetic field presently play an important role in theoretical studies of geomagnetism and the ionosphere.

It will be the aim of the present paper to summarize and discuss our current understanding of a few selected aspects of geomagnetism. Note is first taken of the solar streams of Chapman and Ferraro[4] or of these superposed in time and space, constituting a solar wind.[5,6] The interaction of a solar stream with the magnetosphere is next discussed, with special attention to injection and acceleration of solar stream plasma along the boundary of the magnetosphere. Contributions of hydromagnetic shock waves to the energy of the particles in the magnetosphere are also very briefly noted following Dessler, Hanson and Parker,[7] Kern,[8] Kellogg,[9] and others. The precipitation of particles into high latitudes to produce radio blackouts discussed by Wells,[10] Agy,[11] Hakura,[12] Matsushita,[13] and others, is mentioned together with the auroral and electrojet theories of Martyn,[14] Nagata,[15] Fukushima,[16] Kern,[17] Fejer,[18] and Swift.[19]

Associated motions of the ionosphere, especially the F-region, are noted along with pulsations in the geomagnetic field and conjugate-point phenomena. F-region effects on magnetically quiet days will also be noted with particular reference to the studies of Ratcliffe,[20] Hirono and Maeda,[21] and others; included will be some remarks on dynamo theories of the E-region. There also were early suggestions by Vestine[22] and Wulf[23] that the dynamo theory or fluid mechanics of the magnetosphere might give rise to magnetic disturbances, through separation of charge by ionospheric motions such as zonal winds, with a consequent generation of electric fields and accelerations of particles in the polar ionosphere. Vestine also suggested that hydromagnetic waves might be propagated within solar streams from sun to earth, eventually producing effects at ground level.[22] The hydromagnetic treatment of magnetospheric phenomena is also noted following Axford and Hines.[24]

II. Geomagnetic and Ionospheric Disturbances Associated With Solar Streams

It is well known that disturbances at ionospheric levels, such as magnetic crochets and solar radio blackouts are often successfully linked to solar flares.[25] It is also well known that other ionospheric disturbances, and geomagnetic and auroral effects appear a day or so after a solar flare. This time interval corresponds to the travel times of particles of a few hundred electron volts between the sun and the earth. During great solar flares, protons and other particles with energies approaching tens of billions of electron volts are known to arrive at ionospheric levels. These produce polar radio blackouts, which appear a number of days each year. On occasion, particles presumably of solar origin have penetrated to ground level, even at the equator, where the energy requirements for penetration are extreme. These spectacular effects of high-energy particles, though very interesting, contribute a much smaller total energy than do the large numbers of lower energy particles impinging on the ionosphere. The latter are thought of as having acquired energy in or near the active solar regions in some manner not yet understood. Until recently even low energy particles incident on the atmosphere were thought to come directly from the sun. But the energy fluxes of such low energy particles measured within the terrestrial atmosphere exceeds those expected from the results of space probes outside the magnetosphere; therefore, a mechanism for accelerating particles within the magnetosphere seems necessary. Particles such as those observed over some months by Mariner II in its flight to Venus have travel times of about a day between the sun and the earth, and the particle fluxes resemble (though not in detail) the solar outflows postulated long ago by Chapman and Ferraro.[4]

III. The Chapman-Ferraro Theory

Figure 1 shows an idealized solar-stream consisting of ions and electrons with temperatures of a few tens of electron volts interacting with the geomagnetic field, as imagined by Chapman and Ferraro. The particles in the stream move radially outwards from the sun, and successive faces of the stream are shown. The interaction of a solar stream with the magnetosphere is shown again in Fig. 2. The geomagnetic field and its contents are compressed, and the solar stream passes by on all sides. It was suggested that particles might enter the magnetosphere on the day side at two singular points, one in high northern and the other in high southern latitudes. The figure also shows electric charges distributed on the boundary on the night side. This charge distribution will give rise to an electric field within the magnetosphere. Crossed with the upward directed field lines of the terrestrial dipole (at the equator), such an electric field would drive particles towards the earth and into the magnetosphere and radiation belts. We shall consider this charge distribution later in connection with the results of Explorer XIV for electron fluxes in the nighttime magnetosphere.

Since some magnetic disturbances are measured at ground level every day, streams of varying density and particle energies are probable. Thus, solar streams must be considered as irregular, and their interactions with the magnetosphere are probably nonlinear, even for the initial phase of a storm that was worked out analytically by Chapman and Ferraro. This circumstance has been discussed by Parker,[5] Obayashi,[26] Elliott,[27] Rossi,[28] and others, though without much analytical detail because of the inherent difficulty of the problem. A substantial advance in information that confirmed some details of the early work was provided by the information on interplanetary plasmas and fields obtained aboard Explorer X,[29] and subsequently by Mariner II observations between the earth and Venus, reported by Neugebauer and Snyder.[30] Figure 3 shows a quiet-day pattern of magnetic field lines for a 300 km/sec solar wind.[31] Both the front of a solar stream and any magnetic fields carried radially outward by the stream become spiral in form--a consequence of the 27-day solar rotation. Consider a single filament A, which we regard as a region of enhanced density in the general plasma flow from the sun. As it overtakes the earth each 27 days, it will increase the compression on the magnetosphere, within which disturbances that resemble one another in some respect will recur every 27 days. A model of this kind will explain recurrence tendencies for ionospheric storms, geomagnetic disturbances, and aurora at roughly 27-day intervals. A possible simple 27-day recurrence of this type near sunspot minimum is shown in Fig. 4 for six solar rotations from September 1943 to February 1944.[32] The large pulse enduring about one hour near midnight, if assumed associated with a density increase such as for A of Fig. 3, would imply a highly persistent and stable feature of the solar wind -- a narrow filament. The advancing face of A at the earth will move with an angular velocity depending on the rate of solar rotation, and the distance r from the sun. If the filament passes the earth within an hour (neglecting time constants of effects due to the stream filament), we can estimate its cross section d. Taking the solar rotation period to be 27 days = 648 hours, $d = (1/648) \times 2\pi \times 1.5 \times 10^8$ km $\sim 1.5 \times 10^6$ km. This small filament thickness is much less than a mean free path in the interplanetary medium, so that preservation of such a filament would require a remarkably stable structure of the stream.

The arrival at the earth of high-energy particles from great solar flares is often associated with a Forbush decrease in galactic cosmic rays. This decrease appears to be brought about by a change in the distribution of the interplanetary plasma and magnetic field.[27,33]

IV. Magnetosphere Boundary

The calculations of Chapman and Ferraro relating to the boundary of the magnetosphere have been extended by a number of workers,[34,35,36] who used various simplifying assumptions. Figure 5 shows results based on calculations of Spreiter and Briggs[34] for a dipole magnetic field inclined to a solar stream. A distribution of charge is shown on the boundary in Fig. 2, in accordance with the Chapman-Ferraro theory of 1933. More recently Chapman and Ferraro have considered that a deeper penetration by protons than by electrons is expected at the boundary, resulting only in a charge separation confined to the boundary.

Any actual distribution of electric charge, such as that shown tentatively in Fig. 2, will clearly affect charged particles within the magnetosphere, and will influence the locations and intensities of ionospheric current systems. The distribution of charged particles in the tail of the magnetosphere will depend directly on the configuration of the resultant electric fields. Figure 6 shows recent results of Frank, Van Allen, and Macagno[37] on the flux densities of electrons of energy greater than 40 kev observed on Explorer XII and Explorer XIV. Note that there is a dearth of energetic electrons beyond about 8 earth-radii. In the absence of particle sources, the direction of $\underline{E} \times \underline{B}$ drift can be inferred to be such as to give an earthward velocity E/B, sweeping particles from the central region of the tail. The magnetic moments of particles will be conserved during such $\underline{E} \times \underline{B}$ drift, so that as the particles are driven earthward into a stronger magnetic field they are also accelerated.

It seems necessary to suppose that, even in a steady state, plasma somehow crosses the magnetospheric boundary from the solar stream, perhaps due to unstable ripples arising in the boundary far out along the tail.[15] The important Helmholtz instability of a plasma moving in contact with a magnetic field was considered by Northrup,[39] who showed that growing irregularities might occur. Dessler[40] has suggested that the sunward boundary of the magnetosphere is stable. Far out along the nighttime boundary, however, it seems likely that fluctuations in the solar stream should give rise to exponential growth of irregularities in the boundary, much as in the case of auroral curtains and arcs discussed by Kern and Vestine.[41] Disrupted irregularities or flutes might remain inside the magnetosphere as plasmoids. Such plasmoids will participate in any general pattern of $\underline{E} \times \underline{B}$ drift motion. Some may move earthward into a stronger magnetic field. An adiabatic heating of such plasmoids by compression will follow. Loss of energy from them will contribute to the ionization of the polar ionosphere, as has been remarked by Hines.

Figure 7 shows the polarization of plasma moving in a magnetic field. In an external electric field, $\underline{E} \times \underline{B}$ drift motion leads to a polarization exactly canceling the electric field inside the plasma.[42]

V. Dynamics and Particle Acceleration in the Magnetosphere

Recent observations of the solar wind, made by Mariner II, have failed to show energetic electrons in the quantity required to produce auroras, and insufficient energy fluxes to produce the polar current systems of geomagnetic disturbances.[37] Since measurements were made *en route* to Venus, and therefore survey much of the region near the earth's orbit, it seems necessary to invoke a magnetospheric mechanism that can accelerate a part of the existing charged particles of the exosphere. The alternative possibility of accelerating particles by an atmospheric process has been considered by previous studies, without finding a workable mechanism.[17,43] It has, in fact, been suggested years ago that dynamo effects in the ionosphere might contribute electric fields of interest in this connection.[22,23] In recent years these atmospheric fluid-motion concepts have been applied in considerably greater generality to the whole magnetosphere, assuming energizing to ensue under the influence of the impinging solar wind.[24] The generation of fluid motions by interaction of a solar stream with the magnetosphere, hydrodynamic waves (shock waves) within solar streams flowing from sun to earth, and the hydromagnetic aspects of storms, are discussed in the detailed studies by Dungey,[44] Piddington,[45] Parker,[46] Dessler and Parker,[47] Cole,[6] and, as has already been noted, in the comprehensive statements of Gold,[48] and Axford and Hines.[24] Even earlier, the fundamental concept of magnetic fields frozen into plasma seems to have arisen from storm theory in works of Ferraro, and later by Alfvén. Because of extreme analytical difficulties, many of the various suggestions cannot readily be tested by specific and detailed calculations as was done for the initial phase of storms by Chapman and Ferraro. Accordingly, it appears likely that major clarifications of the magnetosphere -- ionosphere interactions will follow rocket, satellite and space-probe measurements of particle fluxes, fields, and composition of the upper atmosphere and magnetosphere.

There have been recent suggestions regarding the acceleration of particles, using concepts of fluid mechanics. One of the more interesting approaches is that of accelerating charged particles by hydromagnetic shock waves within the magnetosphere.[7,8,23,42-51] There is today some uncertainty respecting the role of shock waves in producing more than the sudden commencement of storms, because the various space probes have not discovered sufficiently accentuated wave fronts of potential shock waves inside the magnetosphere. However, the description of the sudden commencement as a hydromagnetic shock wave remains cogent.[4,47,48,50,51]

The processes of acceleration actually operative are of considerable interest to radio workers, because particles are presumably dumped from above and into the ionosphere. According to Kern,[17] the interaction of a solar stream with the magnetosphere may give rise to nonequilibrium distributions of energetic trapped particles so that electrons and ions separate (due to gradient and curvature drifts in the nonuniform magnetic field). Such charge separation in the trapped radiation gives rise to electric fields in auroral regions. As shown in Fig. 8, these drive the electrojets of bays and cause dumping of trapped particles that produce radio blackouts in high latitudes such as those described by Wells[10] and others. These points have also been discussed by Fejer,[18] and by Cole.[6]

The resulting electric fields in the E-region of the northern hemisphere will necessarily have a conjugate pattern in the southern hemisphere. The driving emf's, whether north-south or otherwise, must act across a segment of the ionosphere as shown in Fig. 9, due to Fejer.[18] We see that the electric driving forces produce conjugate electrojets at both auroral zones, a point noted earlier by Kern and Vestine.[41] Since mirror-point heights usually differ above conjugate northern and southern points joined by a geomagnetic field line, aurora may appear at one station and not at its conjugate. Also the electric conductivities may differ in the two hemispheres, so that a weak bay in one hemisphere may be accompanied by a strong bay in the other. In the same way, radio blackouts may appear strongly in the hemisphere where mirror points are low near the electrojet, and not at all in the other hemisphere where mirror-point heights are more elevated above ground level. This situation also applies to the flux-tube dynamics of Axford and Hines, and should be considered in discussing the effects of interchange motions in the magnetosphere.

Various suggestions have appeared suggesting that electric fields assist in loading new particles into the Van Allen radiation belts, e.g., see Vestine[52] or Akasofu and Chapman.[51] In fact, in at least one theory of magnetic storms due to Alfvén,[53] it is shown that many details of magnetospheric phenomena can be explained by using electric fields. Alfvén imagined that motion of solar streams across the solar magnetic field gave rise to the requisite electric fields in the vicinity of the earth. In the foregoing discussion on the results of Explorer XIV, we have also noted the possibility of a broad scale electric field, based on Chapman and Ferraro's calculations of the charge distribution at the magnetospheric boundary.

A few comments relating plasma flow to electric fields in the magnetosphere seem appropriate. Axford and Hines[24] note that the fundamental equation governing the motion of a low energy plasma in the magnetosphere is $\underline{E} + \underline{V} \times B = 0$, where losses and conduction in the ionosphere are neglected. We can derive $\underline{E}$ from a knowledge of $\underline{V}$ and $\underline{B}$ in a hydromagnetic medium. The only quantity known in even its grosser aspects is the main-field dominated term $\underline{B}$, and as Fejer has remarked,[18] in the outer magnetosphere $\underline{B}$ is dominated by the presence of currents in the boundary and hence becomes difficult to include in a quantitative theory. It is clear that the boundary conditions for the charge yielding $\underline{E}$ are uncertain. The charge distribution described in III seems able to supply a distribution of electrons resembling that of Van Allen and his colleagues. But the electron flux distribution could, in principle, be supplied by other charge distributions. For example, the Axford and Hines circulation shown in Fig. 10 can be adopted and the charge distribution driving it can be inferred. This in general yields excess charge inside the magnetosphere, and also requires consideration of the nonuniform dielectric constant of the medium and the distorted configuration of the magnetic field B.

From the Chapman-Ferraro charge distribution, we can construct an oversimplified model of the supply of particles with plasma driven forward from far along the tail of the magnetosphere. This flow forward constitutes the primary part of our "circulation" scheme, but return flow, unless outside the magnetosphere (which would require modifying the boundary conditions), is not permitted. Thus the plasma must be either dumped or its energy dissipated within the magnetosphere. This picture contrasts strongly with the Axford-Hines circulation pattern for motions in the magnetosphere (Fig. 10).

VI. Conjugate Point and Other Ionospheric Disturbance Phenomena

The time changes of the F-region and E-region during geomagnetic disturbance are of considerable interest in radio-physics because of their importance in radio communications. It has only recently come to be realized that low energy electrons in the upper F-region probably interchange between hemispheres along geomagnetic field lines. This means that equatorial anomalies in the F-region require interpretation in terms of conjugate point locations, a matter recently discussed in a critical review address by Ratcliffe.[20] A convenient chart of conjugate points given recently by Kern and Vestine[41] is presented in Figs. 11A and B. Some features of similarity as well as dissimilarity in correlations of northern and southern hemisphere stations with solar indices have been noted by Mariani,[54] using noon values of f_oF_2 for two eleven-year periods, 1937-1947, and 1947-1957. For latitudes abo 55°N or S maxima appear in linear regression coefficients connecting number density in the F_2-region with solar parameters. There are also indications of a strong number-density dependence in the annual means of f_oF_2 for nearly conjugate stations in the region 30N to 30S. Mariani attributes these effects to dumping of radiation-belt electrons with energies in excess of 40 kev and fluxes of 10^5 to $10^6/cm^2$ sec (energy fluxes 10^{-4} to 10^{-3} erg/cm^2). His estimates are based on the measurements of low energy electron flux by O'Brien(55,56) and Krasovskii, et al.(57) Mariani does not discuss mechanisms of dumping the particles. However, the local acceleration of trapped particles in the magnetosphere is implied by such dumping. This has been indicated previously by O'Brien,(55,56) Vestine,(58) Chamberlain, Kern and Vestine,(59) and Vestine and Kern.(60) Due to the constancy of a particle's magnetic moment $\mu = (1/2)m\, v_1^2/B$, where m is the mass of the particle, and v_1 its spiral velocity, the mirror field B_m depends on the total kinetic energy of a particle. An increase in the velocity of the particle due to some acceleration mechanism means B_m must increase, : involves a lowering of the mirror point, and a possible dumping of particles. Particles supplied to the radiation belts by the Chapman-Ferraro electric field across the tail of the earth are locally accelerated by $\underline{E} \times \underline{B}$ drift into a stronger magnetic field. The lowering of mirror points due to local acceleration may also be discussed using the second (or longitudinal) adiabatic invariant,(59) and other features of their dynamics can be clarified.

The various phenomena associated by Mariani[54] with the dumping of particles are probably modulated by regular seasonal changes in the orientation of the geomagnetic field with respect to the solar wind as shown in Fig. 5. A direct effect on averages of the annual magnetic variation is apparent in Fig. 12. Season dependent changes in the F-region have been noted.[61] An interesting seasonal variation appears in whistlers.[62] There is also a seasonal effect on the polar-cap distributions of S_q electric currents (Fig. 13), as noted by Nagata.[63] Some of these effects may be related to the seasonal variation on the distribution of a broad-scale electric field within the magnetosphere.

A number of conjugate-point effects involving rapid transient changes or pulsations in the geomagnetic field are associated with the appearance of ionospheric changes, or with aurora. Thus, Harang[64] found regular magnetic pulsations of some minutes period accompanying radio signals returned from the ionosphere. It was noted quite early that pulsations of auroral illumination on occasion have the same period as geomagnetic pulsations. Vestine found intervals of 2-second pulsations by direct timing of an auroral display that lasted nearly an hour in 1933.[65] In recent years these phenomena have been explored extensively and good correlations have been established between magnetically conjugate stations by Campbell and Leinbach,[66] Troitskaya, _et al._,[67] and by Campbell and Matsushita.[68] Geomagnetic pulsations in field noted by a magnetometer aboard Explorer X were also discussed by Ness, _et al._,[69] and a number of writers have presented hydromagnetic theories of such pulsations.[70,71]

Ionospheric effects have also been discussed using models of solar-cycle variations in the upper atmosphere.[72,73] These are also effects due to storms such as those observed by Jacchia[73] and Paetzold and Zschoerner.[74]

An extensive series of papers dealing with general aspects of ionospheric storms in the F-region has appeared.[63,75-78,79-85] These results will not be considered in detail here. There is, in general, considerable temporal agreement between effects noted in the F-region and those in geomagnetic storms. Up to a height of about 200 km, the storm effects are less pronounced. In the F-region a thickening occurs on the first day of a storm, and there is often loss of ionization later, perhaps due to ionospheric heating.

A recent review of some storm effects in the F-region has been given by Somayajulu.[85] He dealt especially with effects noted during three severe magnetic storms. An interesting feature was the noontime depression in the height of the F2 maximum of about 100 km at Washington, D. C., on the storm days as compared with quiet days; other changes are indicated in Fig. 14. For 42 storms, Matsushita[83] studied average aspects of the electron density N, the total ion content in a vertical column of unit area, and the electron content below various heights of the ionosphere. He analyzed these data according to storm time and SD variations at 8 stations. Electron-density profiles on both storm and magnetically-quiet days were plotted against height and latitude. For the SD variations, most of the results in middle latitudes seem explicable in terms of electric fields of polar electrojets, operating on the ionosphere in combination with the geomagnetic field. For the storm-time variation, Matsushita found an apparent increase in ionization occurring above the maximum height of the F-region at the beginning of the main phases of storms. He suggests that this ionization may diffuse down the magnetic field lines and, under influence of gravity and pressure gradients, move to regions above low-latitude stations. In slightly higher latitudes a rapid decay process associated with temperature increases in the upper F-region in summer may occur.[20,84]

The final figure (Fig. 15), showing variations in phase height of 16 kc/sec waves, has been discussed by Ratcliffe and Weekes.[84] The effects shown have been interpreted in terms of change in D-region height. The figure also shows that during storms and during the after field of storms there are nighttime changes of special interest.

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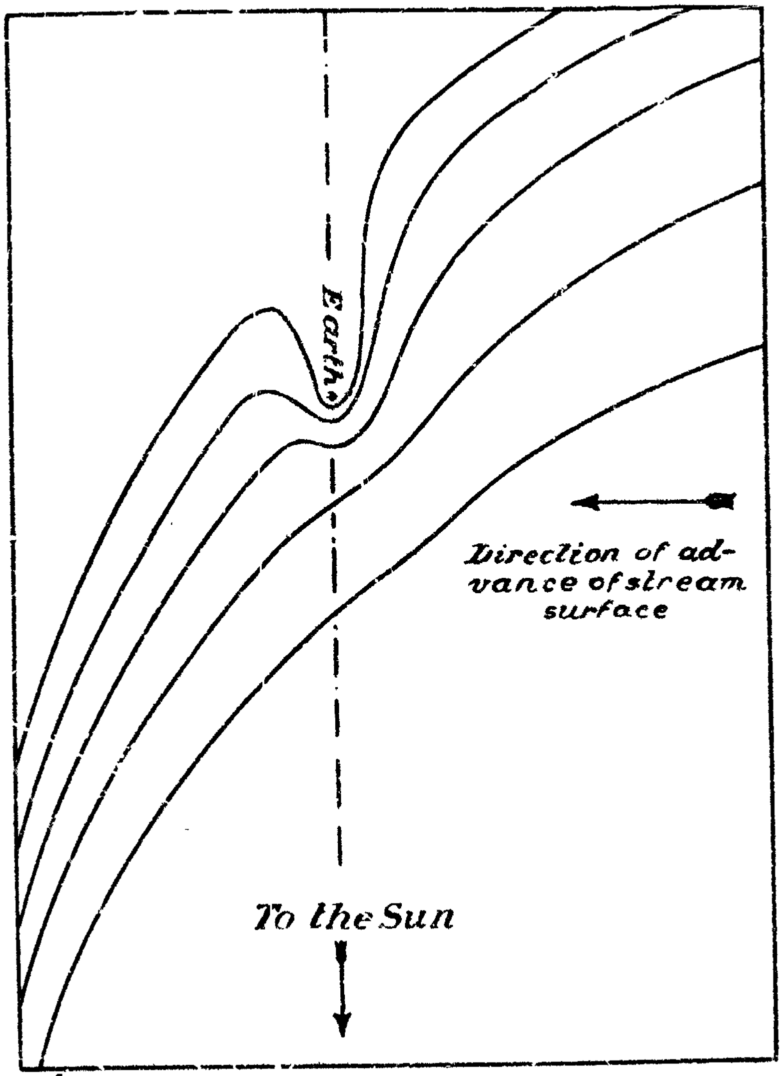


Fig.1--Successive equatorial sections of the surface of advancing stream

(after Chapman and Ferraro)

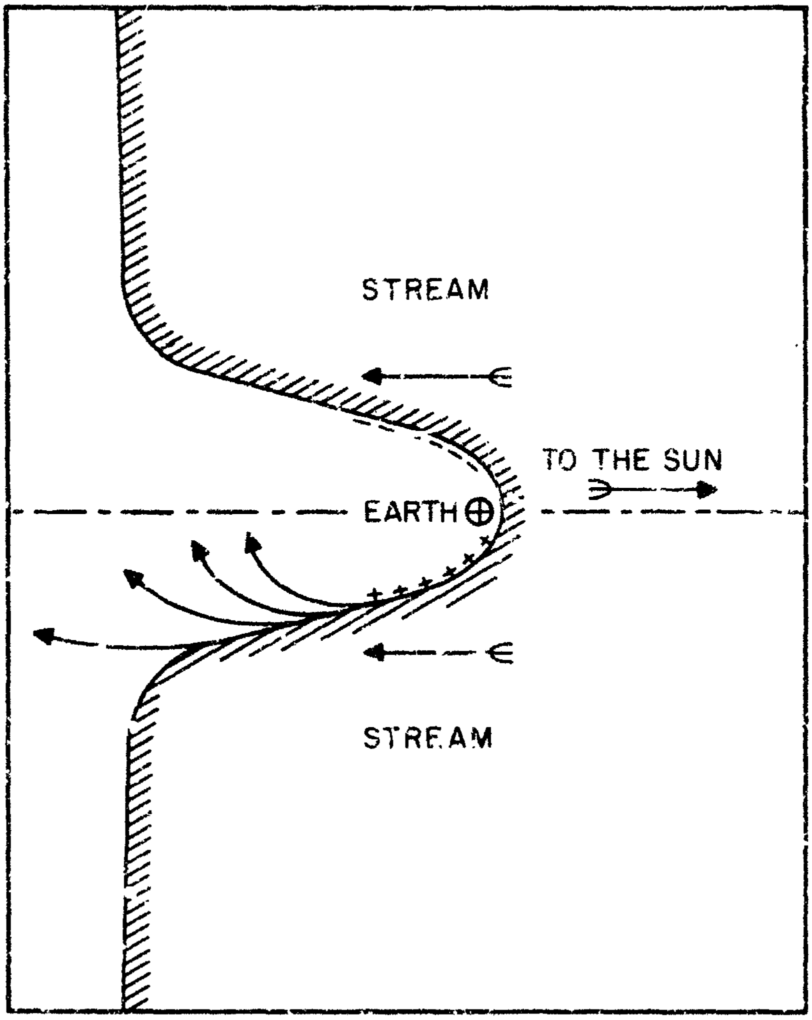


Fig.2--Equitorial section of magnetospheric boundary (after Chapman and Ferraro)

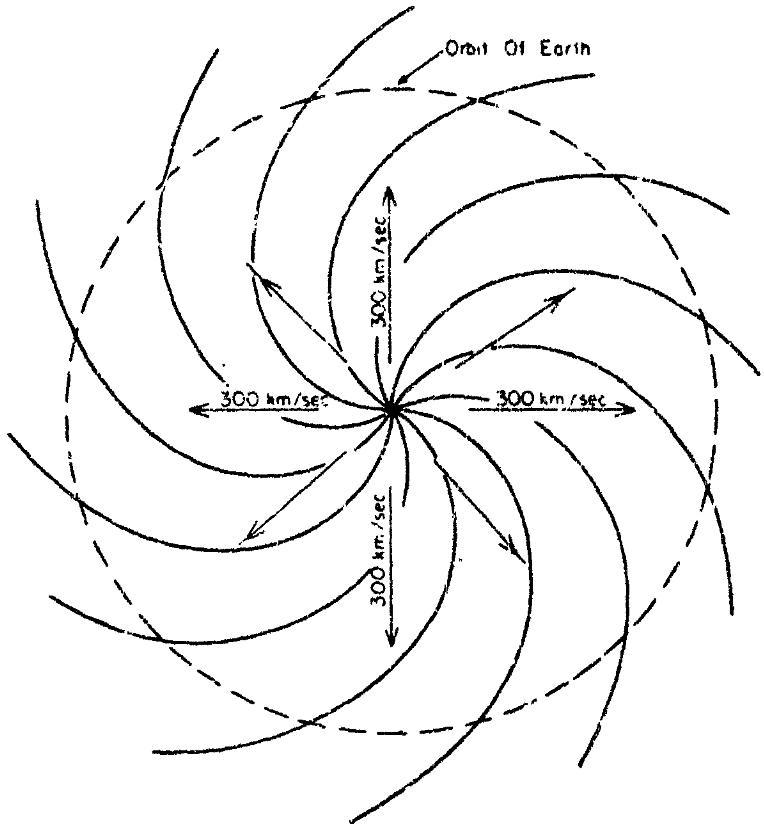


Fig.3--Extension of the general solar field by an idealized uniform quiet-day solar wind of 300 km/sec in the solar equatorial plane

(after Parker)

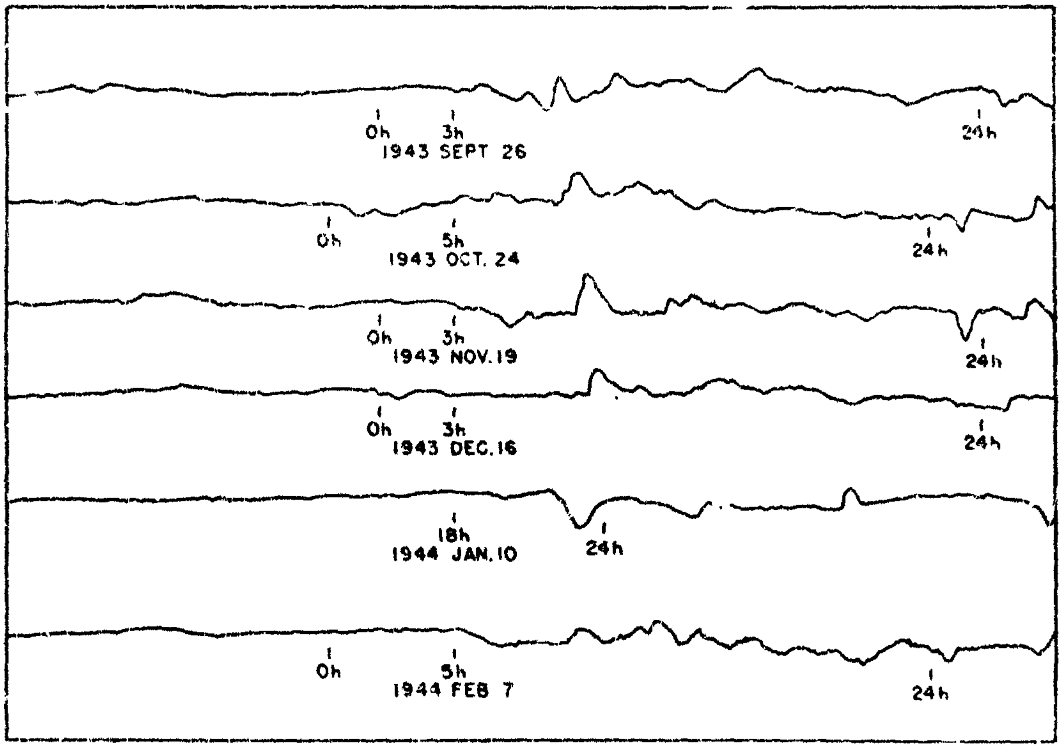


Fig.4--Tracings from the records of the horizontal component of the earth's magnetic field recorded at Mount Wilson, showing portions at the time of six abrupt onsets

(after Wulf and Nicholson)

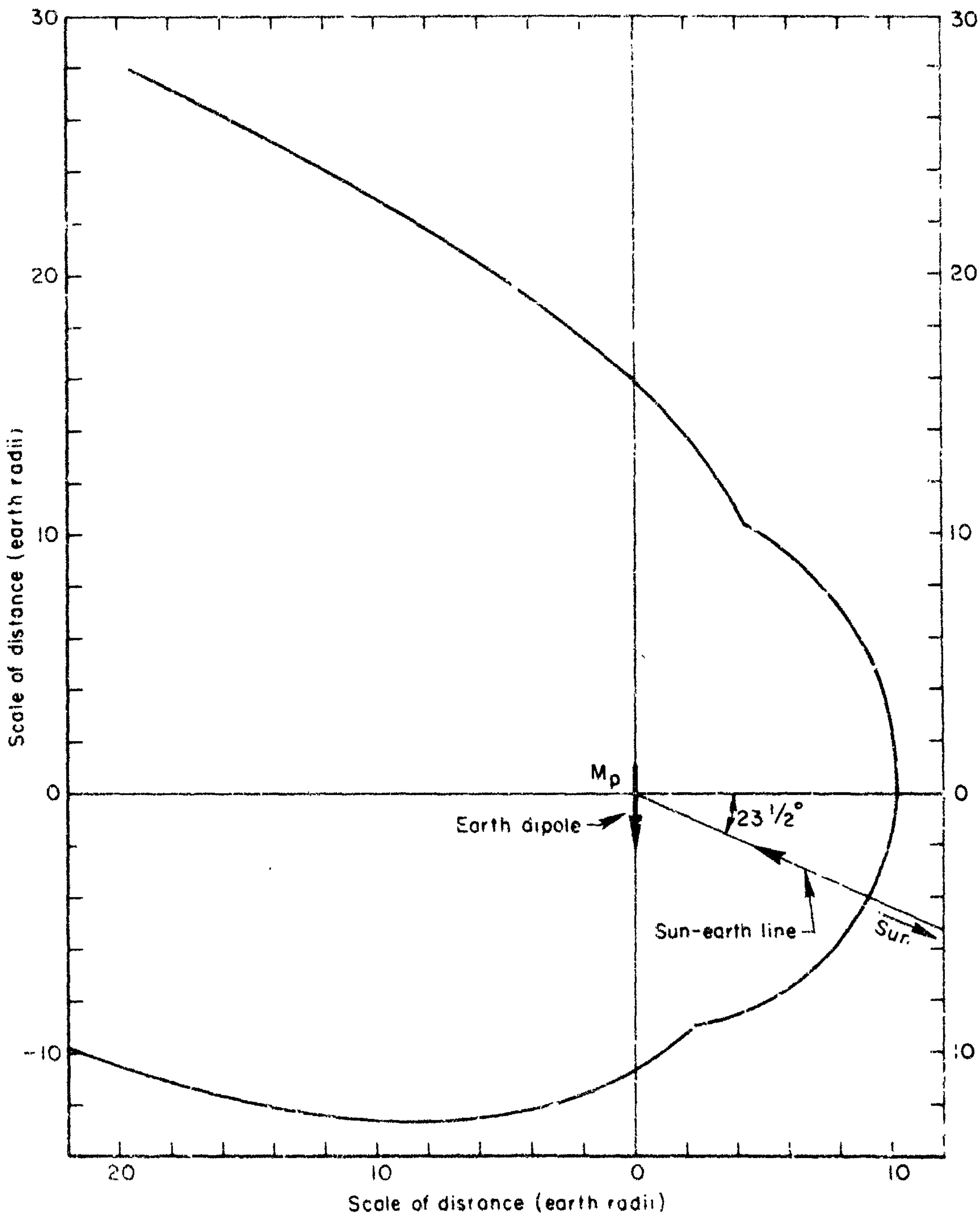


Fig.5--Form of boundary of magnetosphere in the meridian plane containing dipole axis and sun-earth line, winter solstice

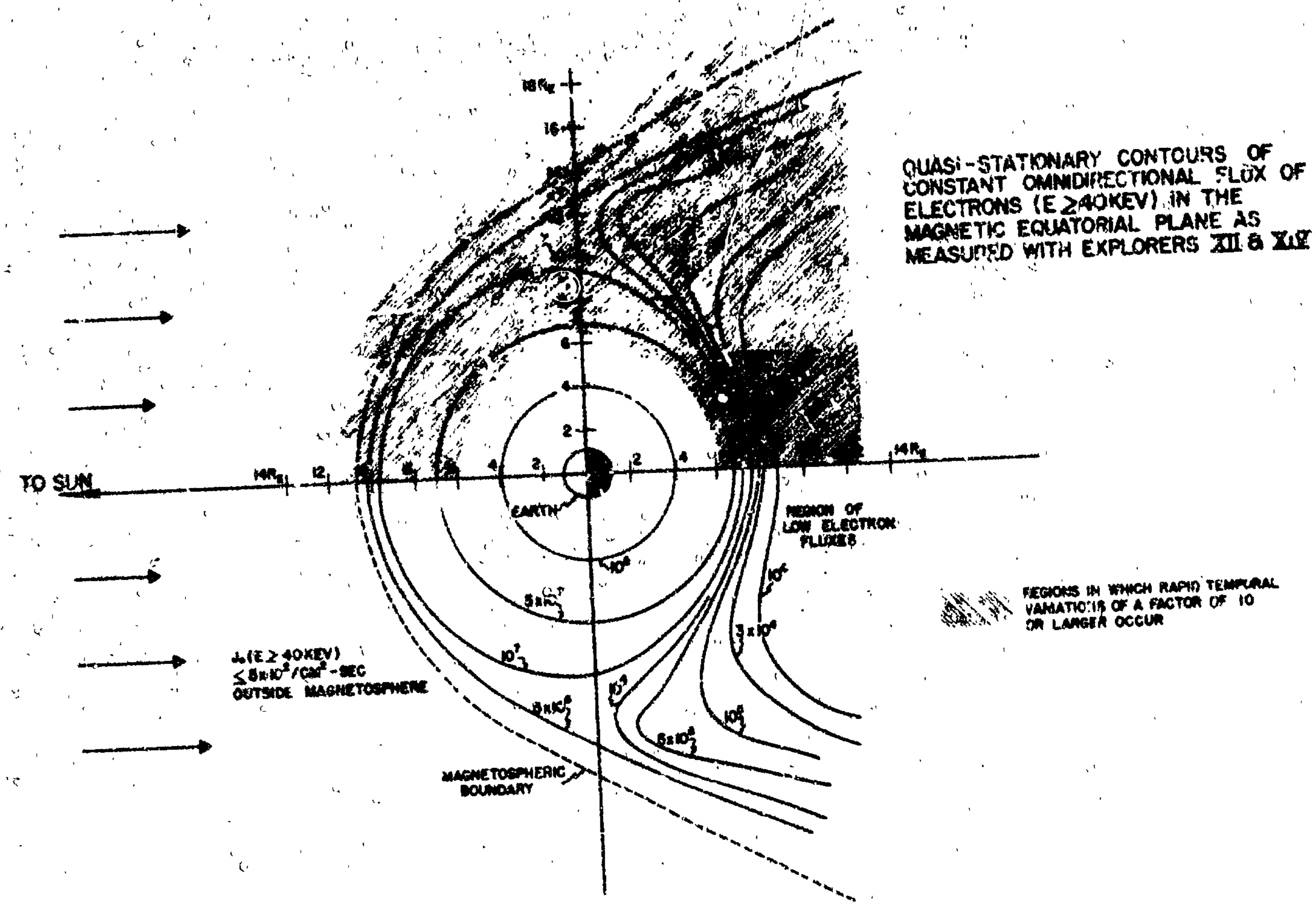


Fig.6--Quasi-stationary contours of constant omnidirectional flux of electrons ($E \geq 40$ Kev) in the magnetic equatorial plane as measured with Explorers XII and XIV

(after Frank, Van Allen, and Macagno)

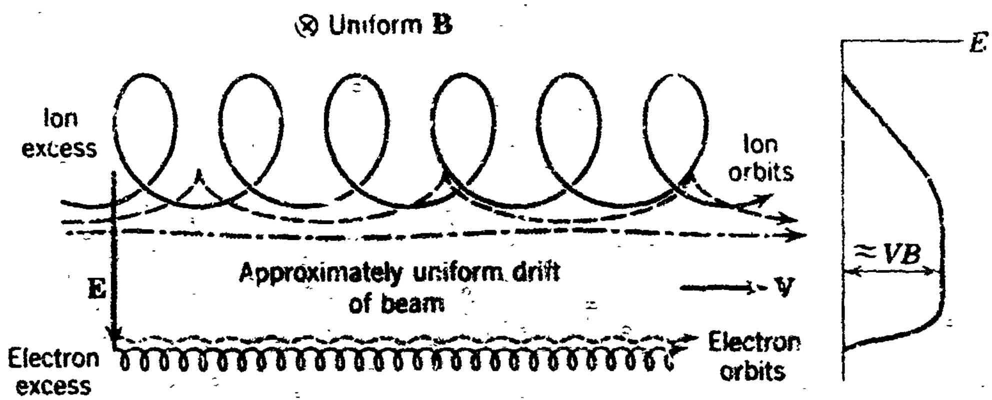


Fig.7 -Schematic representation of typical particle orbits and magnitude of electric field in a dense beam of ions and electrons crossing a magnetic induction B. The beam is assumed to be thick in the B-direction.

(after Rose and Clark)

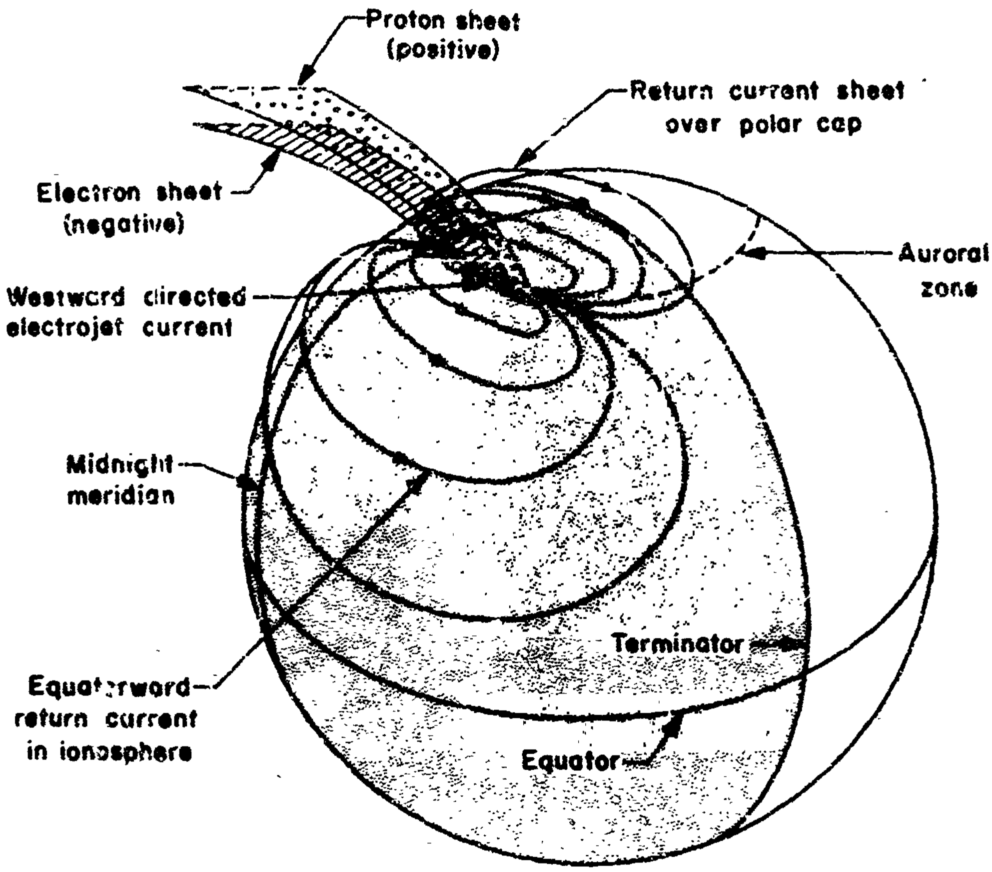


Fig. 8 --Polarization of radiation incident in the auroral zone and Hall conduction polar-electrojet currents

(after Kern)

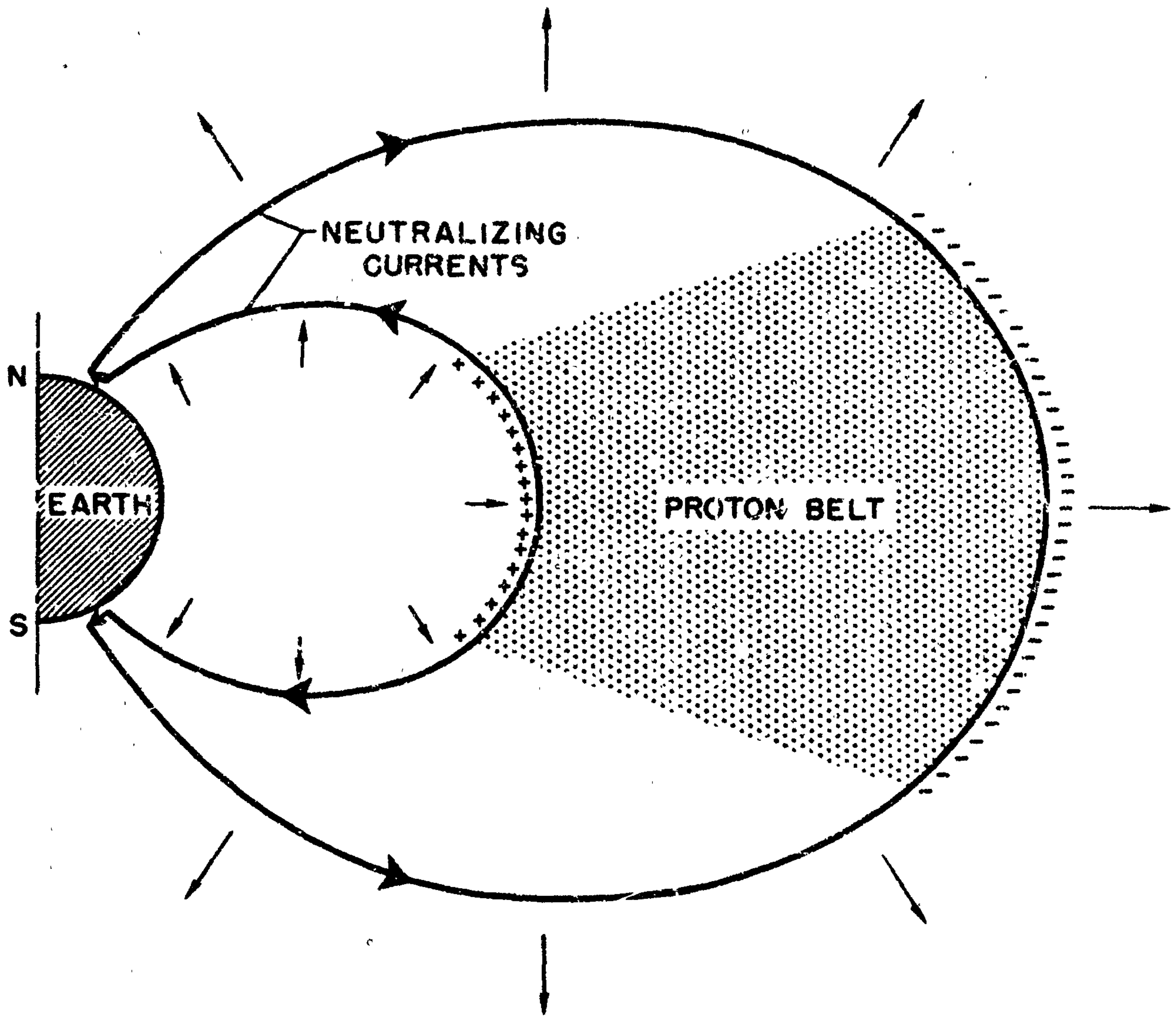


Fig. 9 --Current and electric fields in magnetosphere during magnetic bay
(after Fejer)

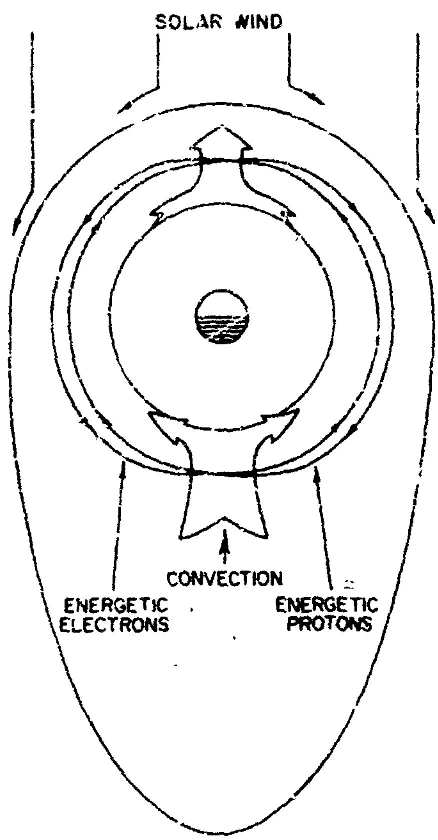
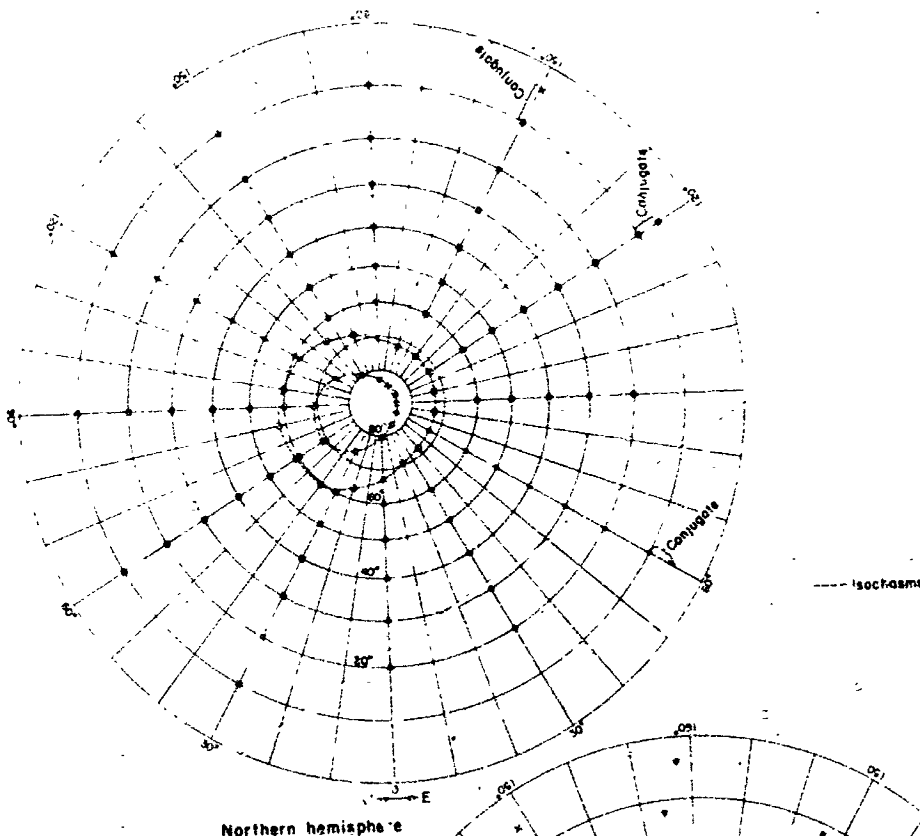


Fig.10 --Theoretical circulation of the magnetosphere
(after Axford and Hines)



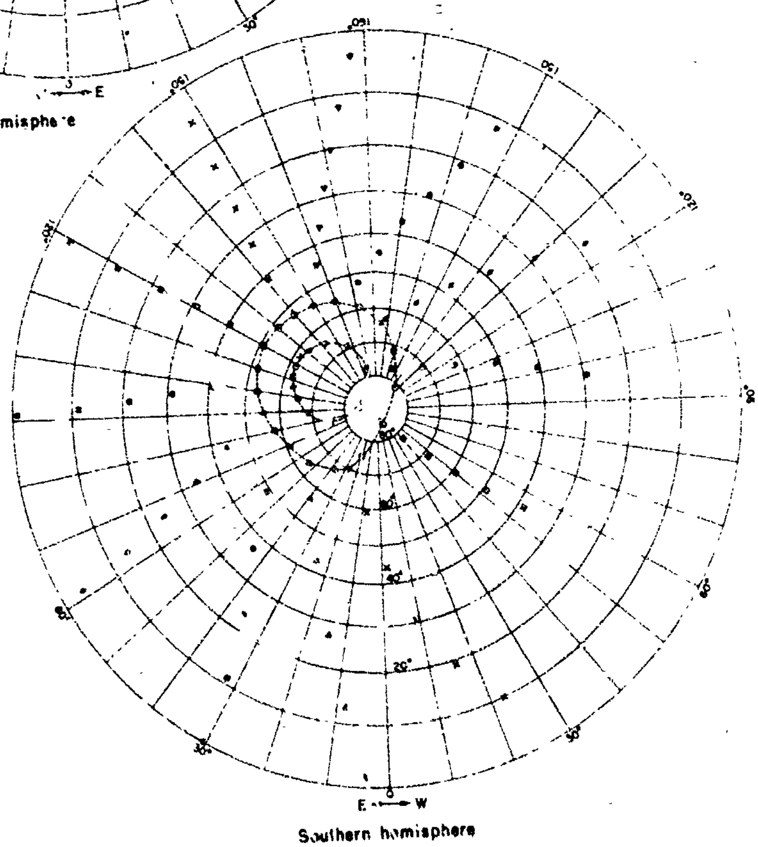


Fig. 11A Conjugate points derived from the analysis of Vestine and Sibley; southern hemisphere points conjugate with uniform grid of northern hemisphere points (auroral isochasms are shown)

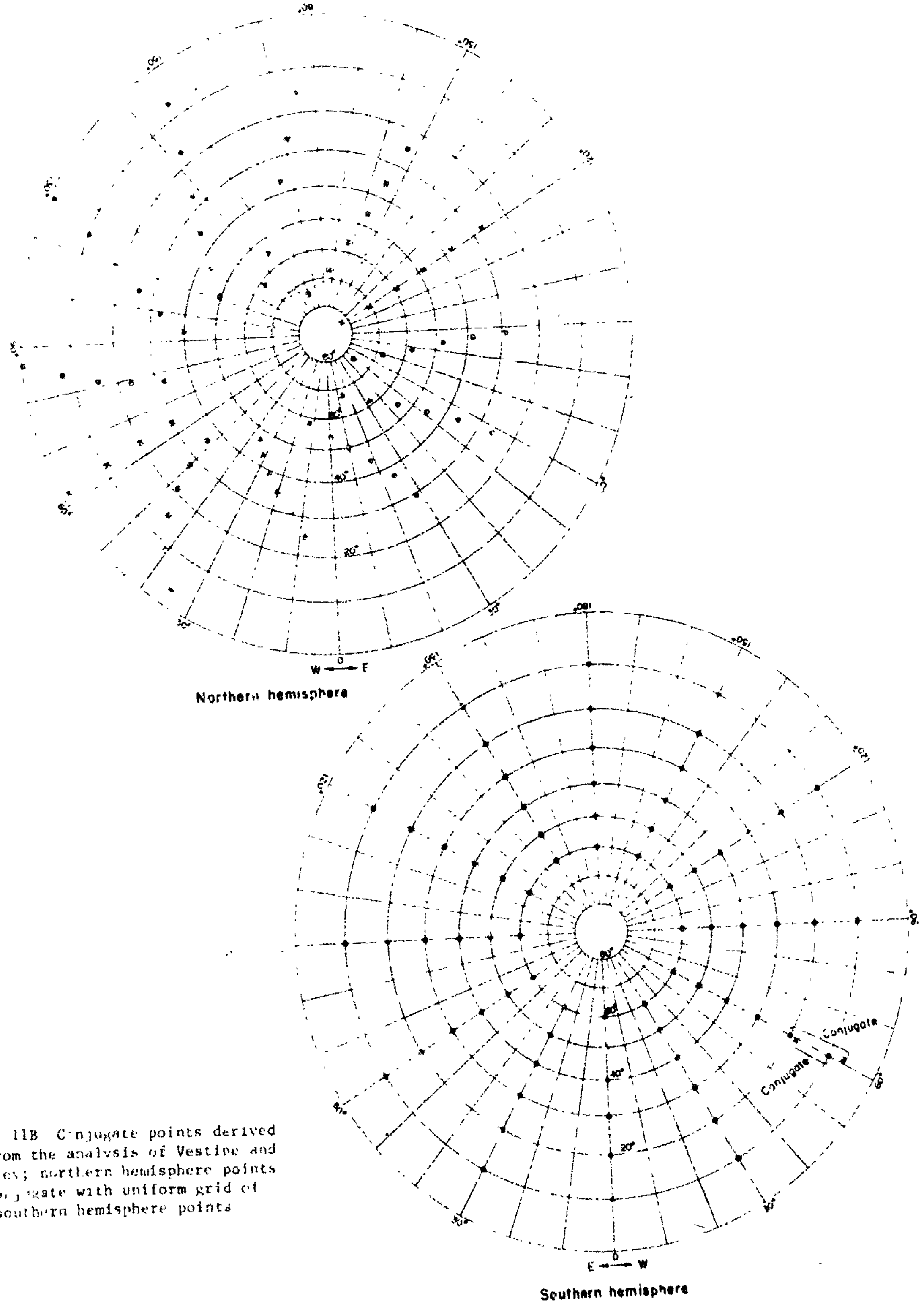


Fig. 11B Conjugate points derived from the analysis of Vestine and Sibley; northern hemisphere points conjugate with uniform grid of southern hemisphere points

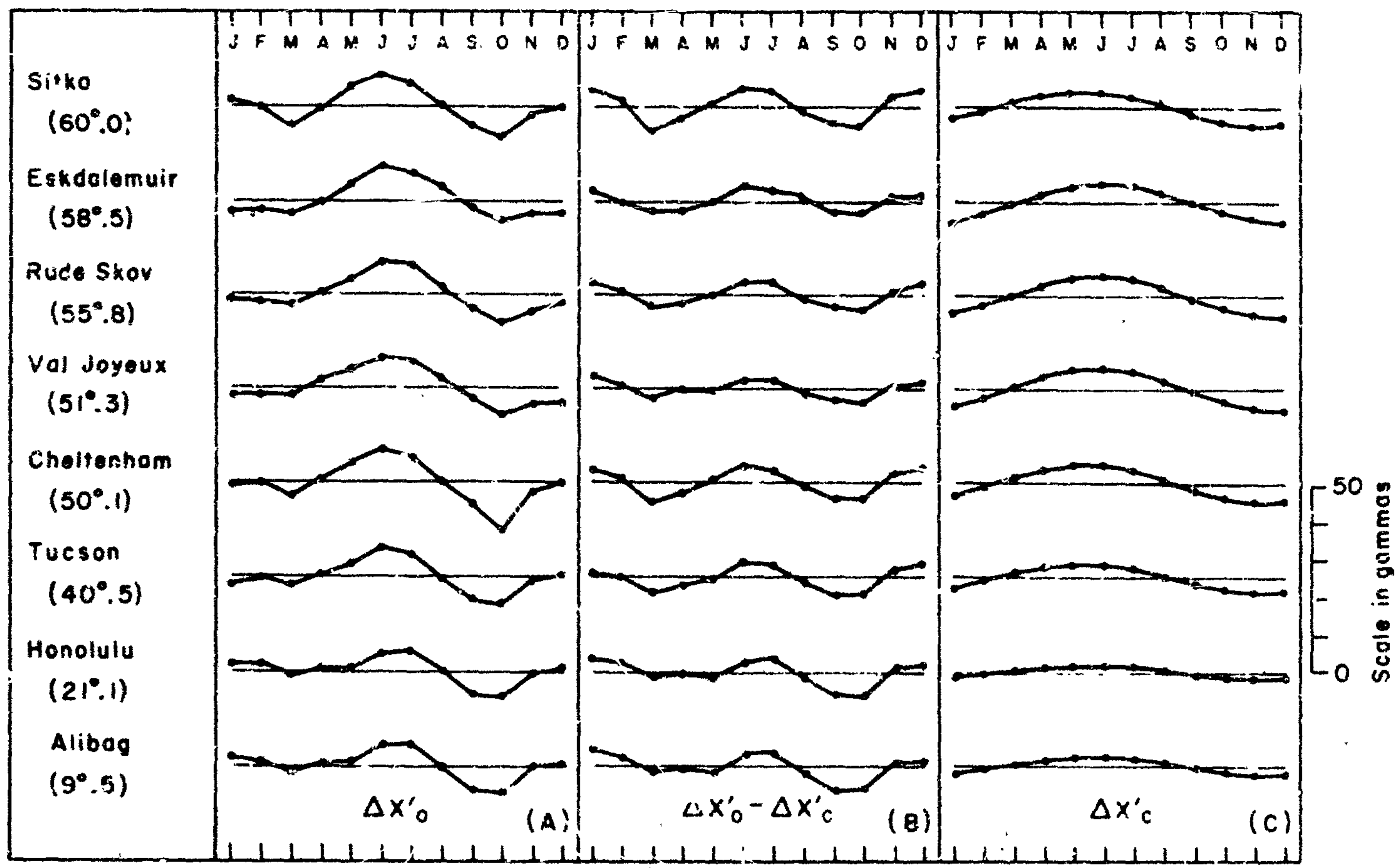


Fig.12--Average annual variation of X'-component, 1911 to 1935

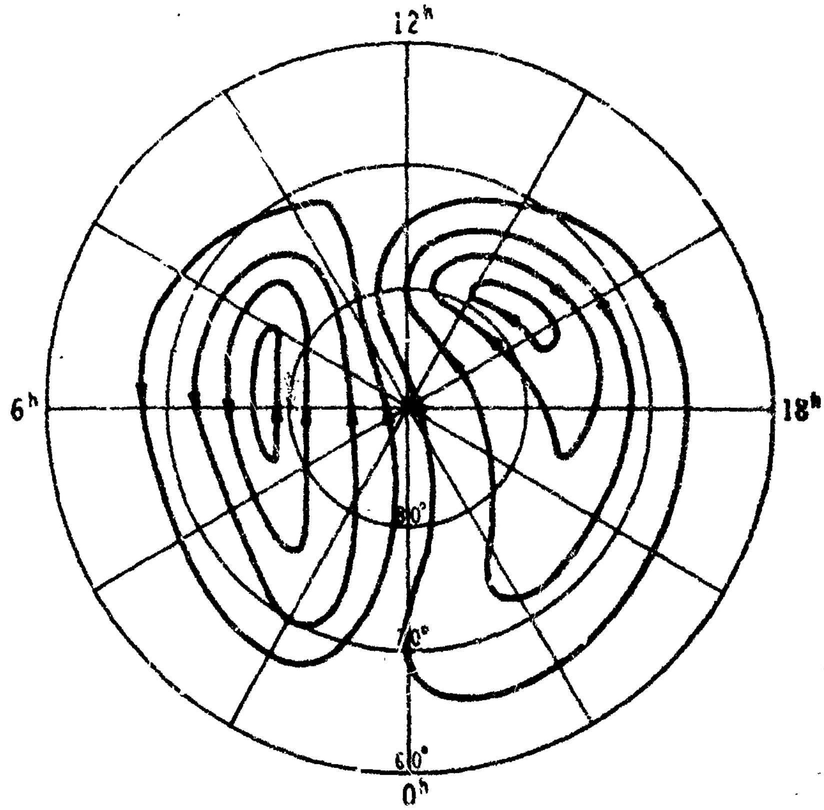


Fig.13--The additional sunlit polar cap current pattern. Sq(SP) (Electric current between adjacent lines is 2 x 10^4 amp)

(after Nagata)

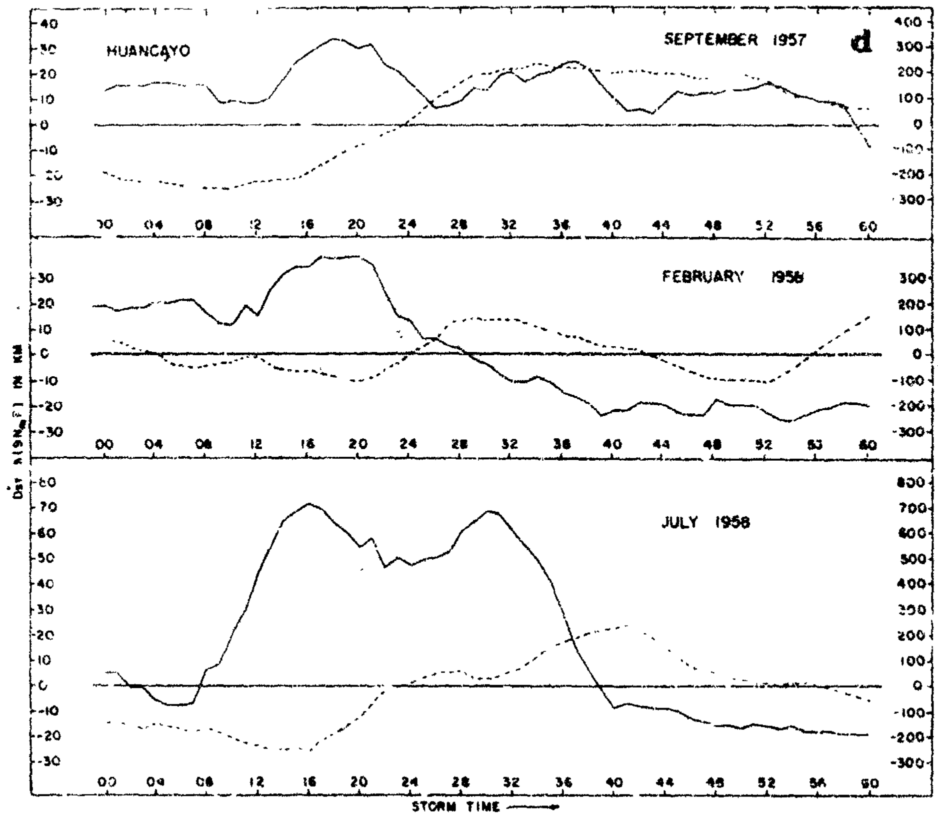


Fig. 14 -Dst variations of the maximum electron density of the f region (broken line) and the $h(0.9N_mF)$ during storms

(after Somayajulu)

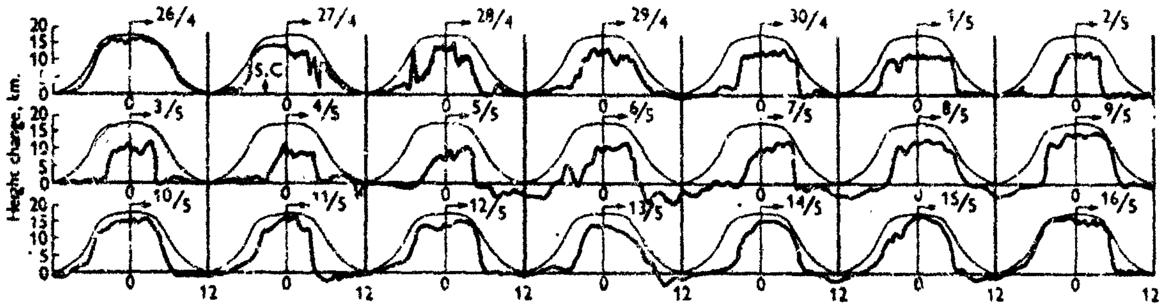


Fig.15 --Variations in phase height of waves of frequency 16 kc/sec. Observed at Cambridge, 1956

(after Ratcliffe and Weekes)

VAN ALLEN RADIATION: EXPERIMENTAL RESULTS

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ABSTRACT

The experimental knowledge and theoretical understanding of Van Allen radiation in the outer regions of the magnetosphere are summarized. The region out to geocentric radial distances of 10 to 15 earth radii is occupied by geomagnetically-trapped protons and electrons, whose energy spectra generally get softer further from the earth. Typical electron fluxes are $\sim 10^7$ to 10^8 particles $cm^{-2} sec^{-1}$ for electrons with energy above $\sim$ 40 kev. Typical proton fluxes above $\sim$ 100 kev are of the same order of magnitude. The electron fluxes are larger temporal fluctuations than the protons, with particularly pronounced changes during geomagnetic storms. The particles are trapped within the ordered magnetosphere within geocentric radial distances less than about 10 earth radii. Towards the outer boundary of trapping are generated intense fluxes of electrons that cause auroras. These electrons are too numerous to be simply old Van Allen electrons, but the interrelation of Van Allen and auroral electrons is unclear. There is no theory that even begins to explain the source of Van Allen or auroral particles.

VAN ALLEN BELTS - INTERPRETATION

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(Paper is not available for publication)